Using microtomography in geosciences

Ex: Studying fluid and mass transfers in porous geomaterials with application to CO_2 underground storage, …

Philippe Gouze

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with application to CO_2 underground storage, …

Philippe Gouze (Transport in Porous Media research unit)

- **CNRS** (Governmental Research Institute): ≅ 20000 people; all disciplines

- ***Géosciences Montpellier :***
  Research covers a large range of topics in geology, geophysics and hydrogeology
  ≅ 150 people (1/3 academics, 1/3 CNRS), publications ≅ 130/yr, PhD defense ≅ 15/yr.

  Based at the ***University of Sciences - Montpellier***
  ≅ 4500 people (3/5 academics), ≅ 16000 students, 7 departments (≅ 90 research units)

To make a long story short:

CO_2 storage (i.e. massive injection of CO_2 in underground reservoirs or aquifers) produces highly aggressive fluids and strong mechanical stresses.

The standard *reservoir* models developed, for instance, for the oil industry cannot handle these conditions.

Many coupled mechanisms taking place in these conditions are still poorly known.

The acceptability (both in term of industrial feasibility and risk assessment) of this technology requires sound predictive models.

The main issues are:

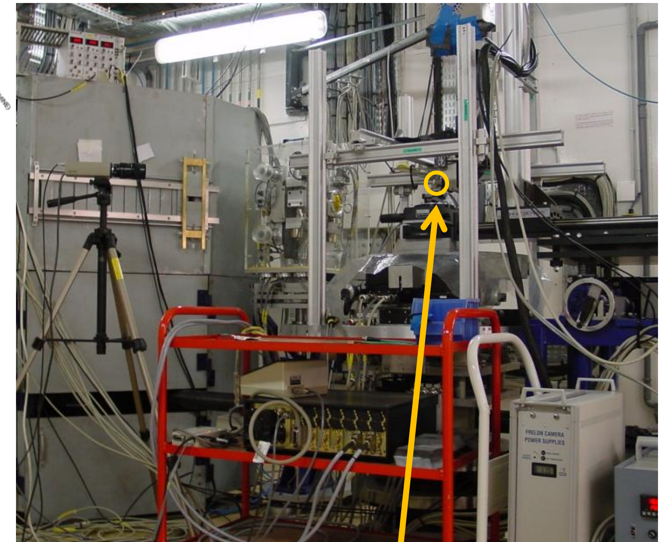
- Identifying all the mass transfer processes
  (ex: fluid-rock reactions)
- Measuring parameters for feeding the numerical models
  (ex: permeability, dispersivity)
- Determining the functional relationships required for coupling flow, transport and reaction in the numerical models
  (ex: porosity-permeability laws)

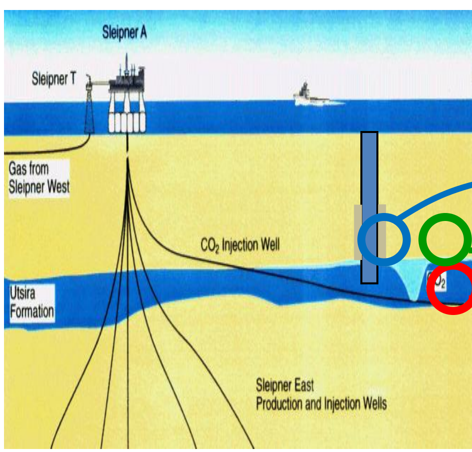
<u>In this context X-ray microtomography is used to study</u>

Media composition (rock-forming minerals and void distribution)
Media structure *versus* flow properties
Media structure *versus* solute transport & reactions
Structure of fluid-fluid interfaces (multiphase flow)
Media structure *versus* mechanical properties
…

media = porous media or fractured media
= reservoir rocks, caprocks, well cement, …

Typical study protocol

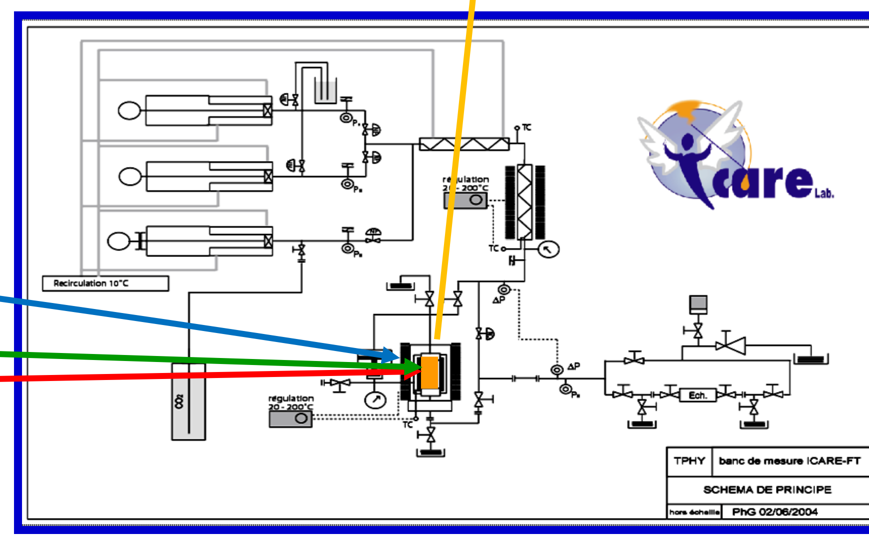




Cement samples

Caprock samples

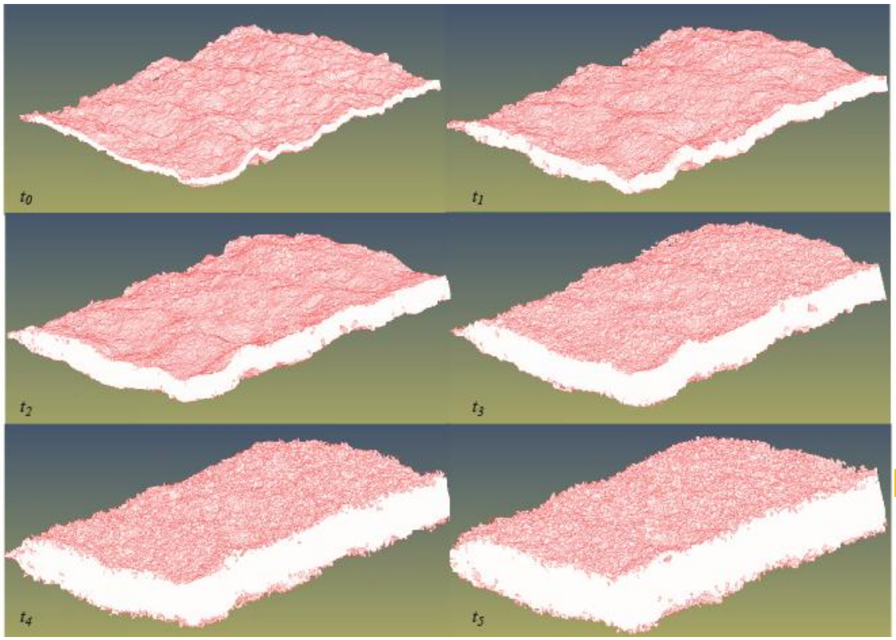
Reservoir rock samples

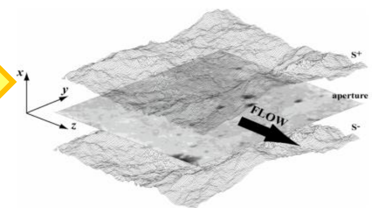


Reproduce *in situ* conditions

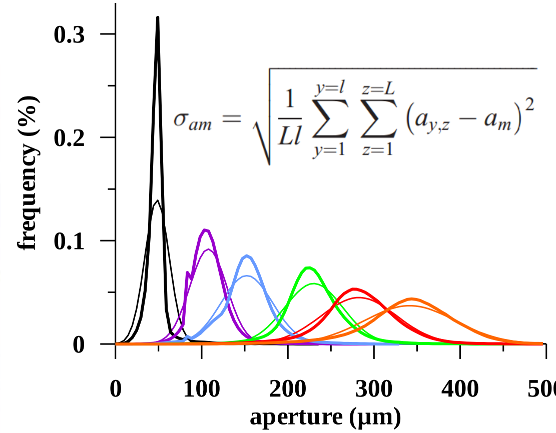
fractures

Rough fracture dissolution : geometrical properties *versus* aperture increase





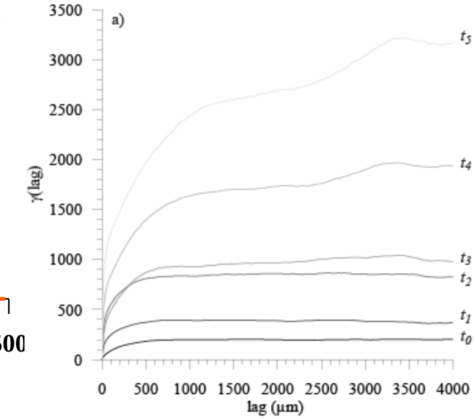
Aperture distribution



$$\sigma_{am} = \sqrt{\frac{1}{Ll}\sum_{y=1}^{y=l}\sum_{z=1}^{z=L}\left(a_{y,z} - a_m\right)^2}$$

Aperture spatial correlation

$$\gamma(\delta) = \frac{1}{2n}\sum_{i=0}^{i=n}\left[a(z_i+\delta) - a(z_i)\right]^2$$

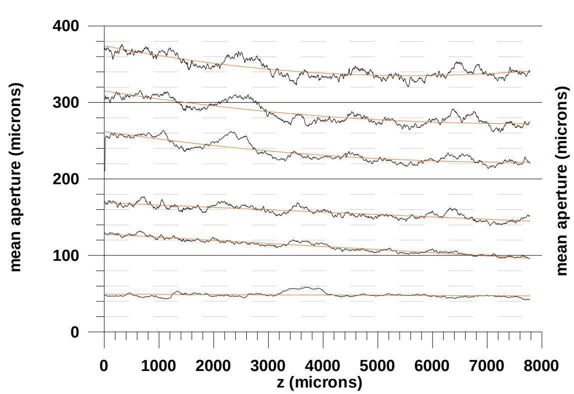


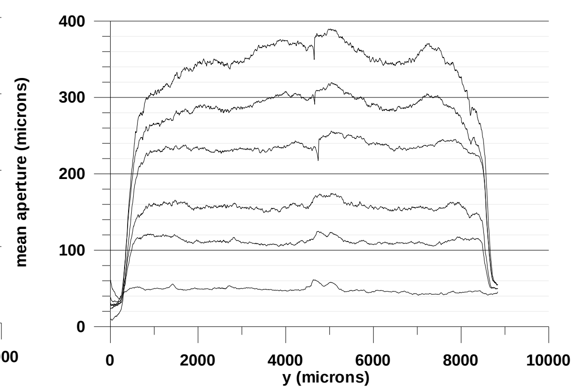
Many other parameters …

$$\tau = \frac{1}{l}\sum_{y=1}^{y=l}\frac{L'}{L} = \frac{1}{l}\sum_{y=1}^{y=l}\frac{\sum_{z=1}^{z=L}\sqrt{(h_{z+1}-h_z)^2 + \Delta z^2}}{L}$$

$$\Re = \sqrt{\frac{1}{L\,l}\sum_{y=1}^{y=l}\sum_{z=1}^{z=L}\left(h_{z+1}-h_z\right)^2}$$

Average aperture // and ⊥ to flow

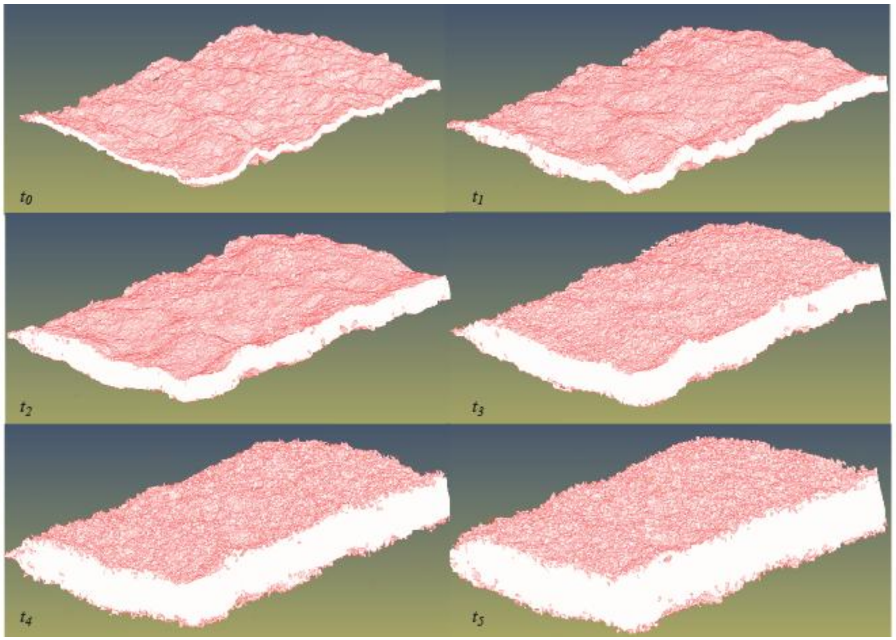


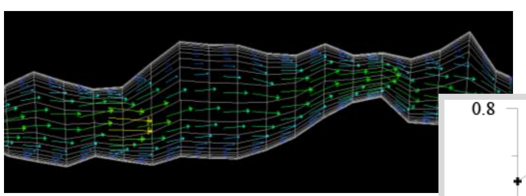


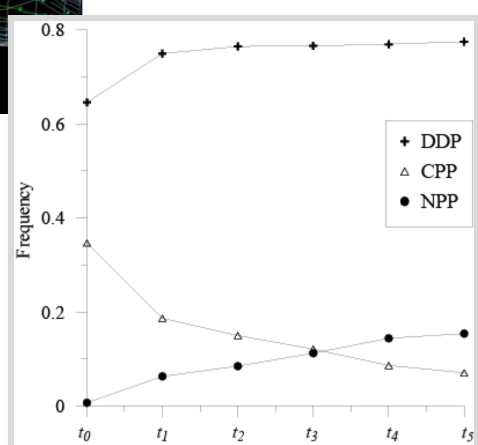
(Noiriel and Gouze, JH, in review)

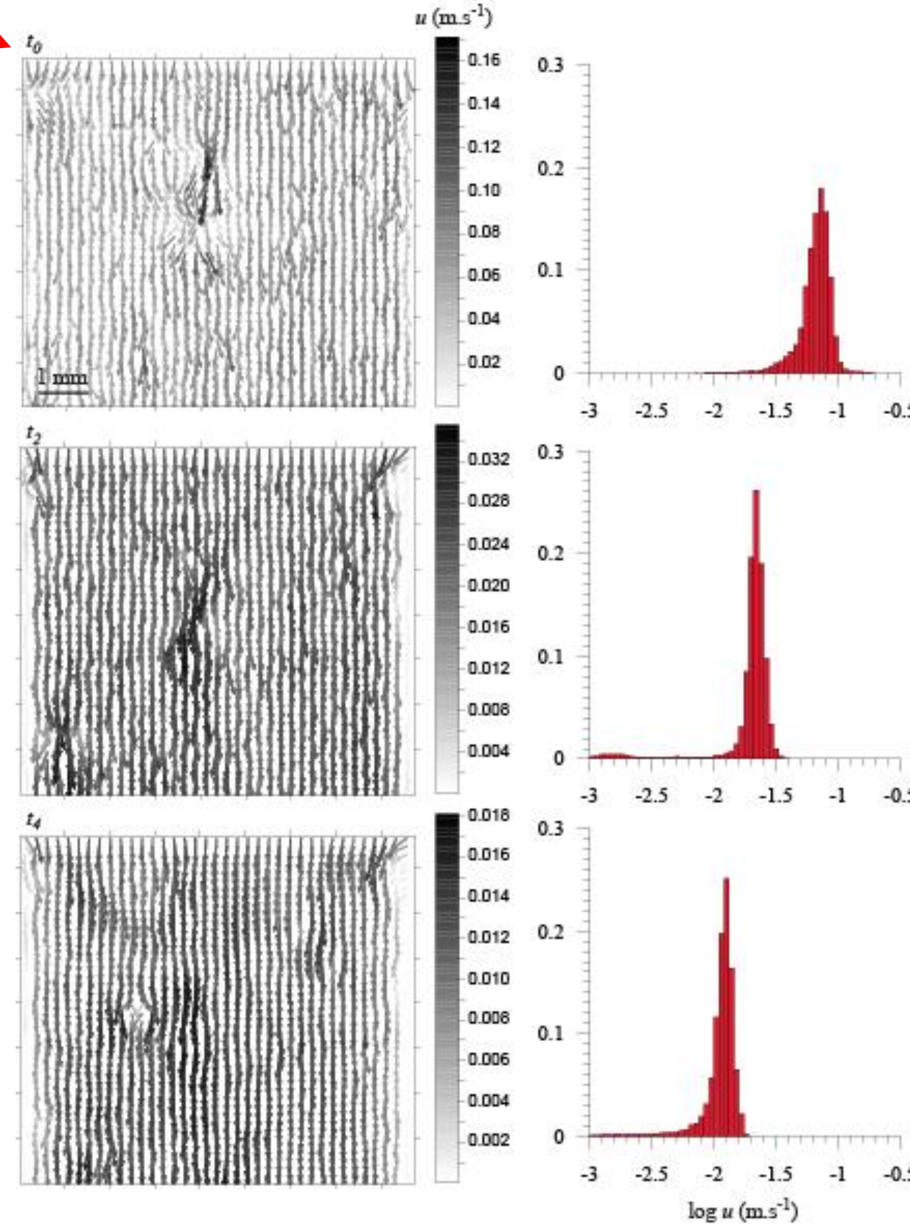
Rough fracture dissolution : flow field properties *versus* aperture increase

Solve Stokes equation



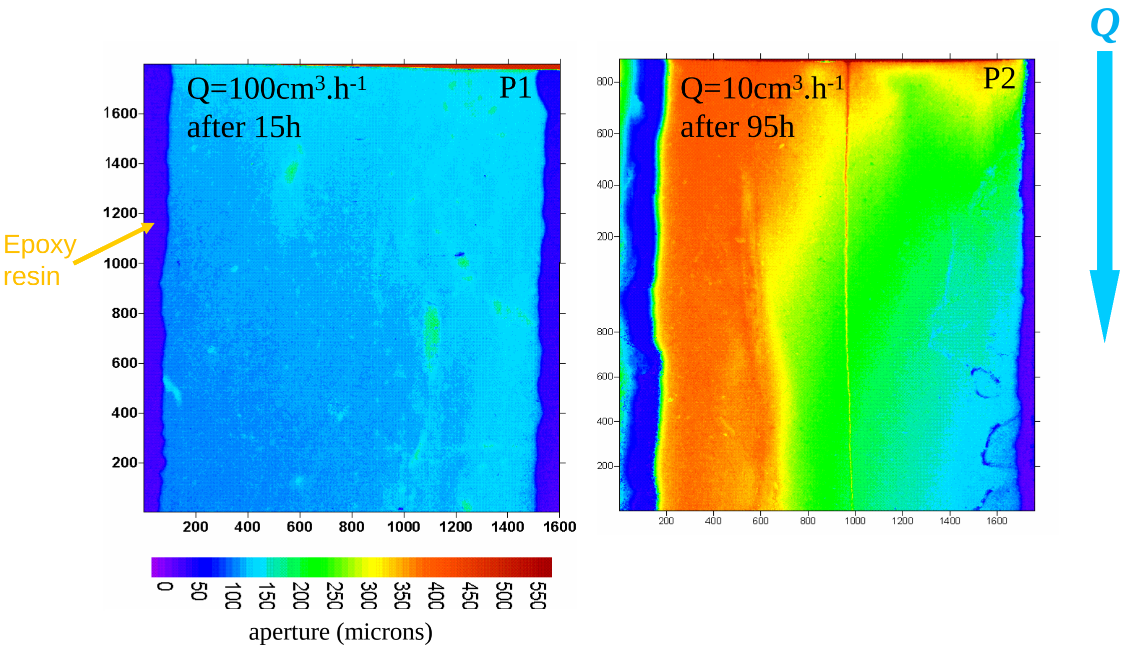


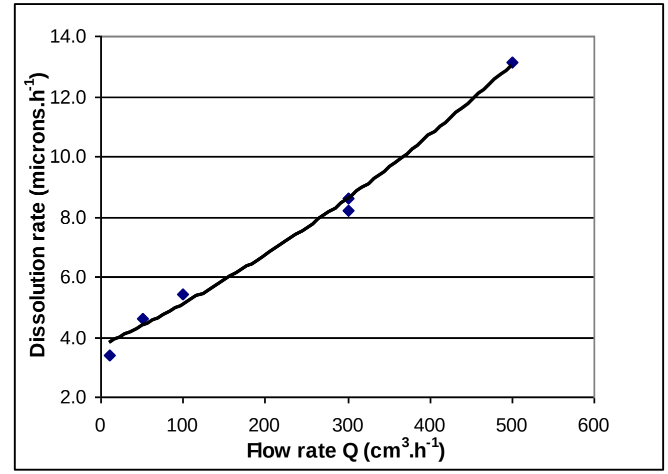


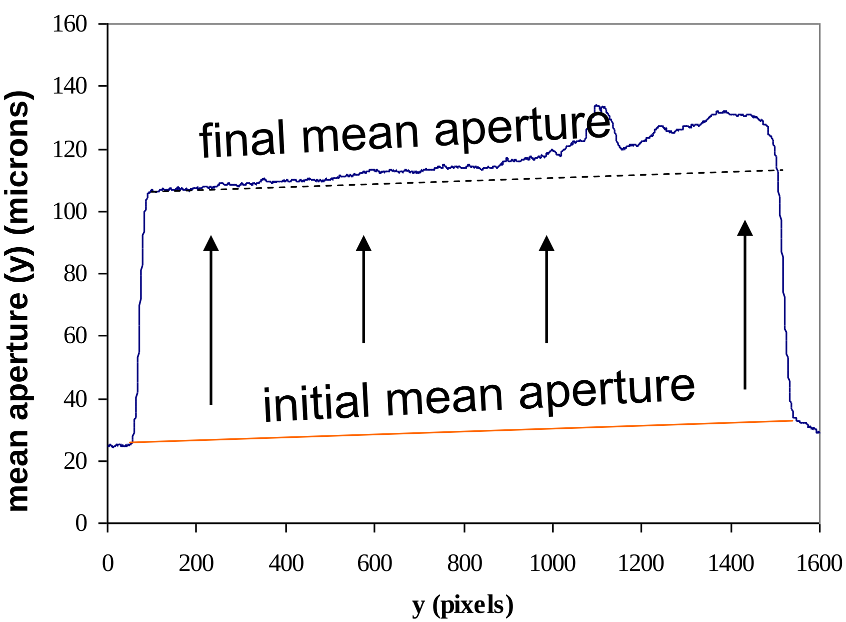


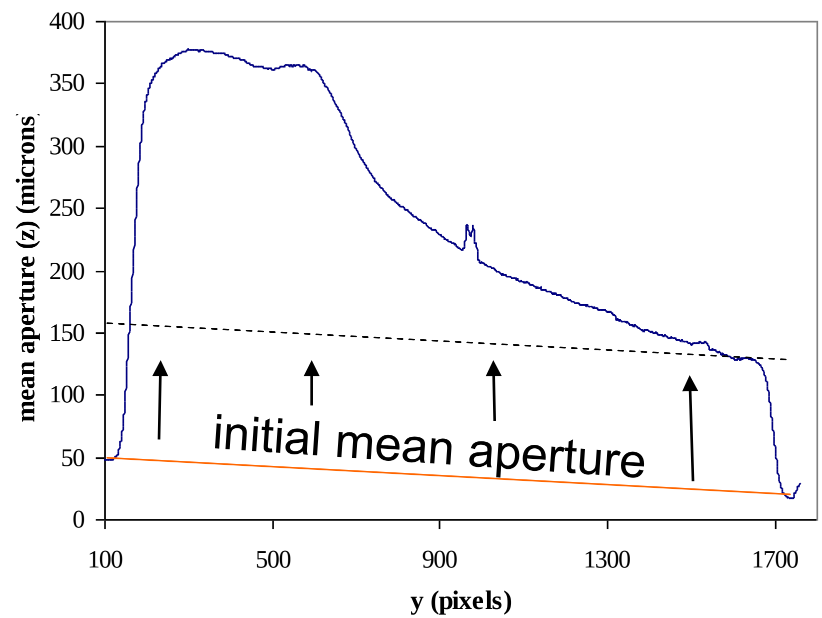
(Noiriel and Gouze, JH, in review)

Planar fracture (sawn) : localization effects and dissolution rate *versus* *Q*



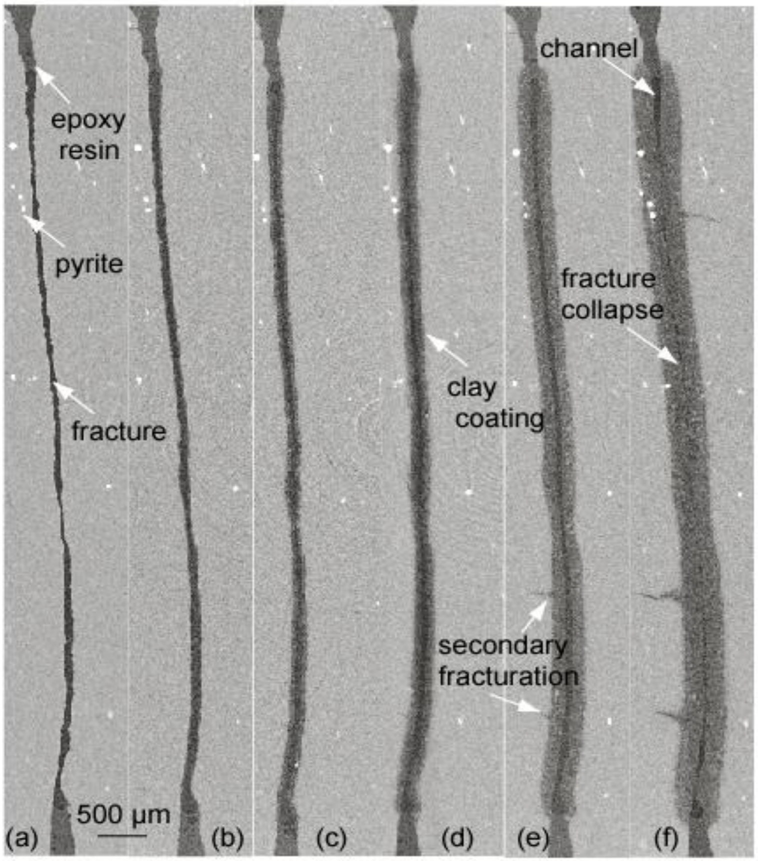






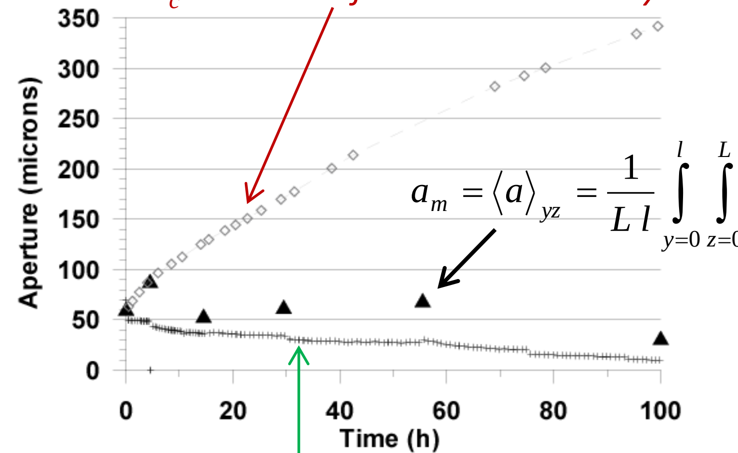
(Gouze and Noiriel , unpublished)

Rough fracture dissolution with coating growth (marl)



$$a_c = a_0 + \frac{Q}{A_s} \times \left(\upsilon_{dol} \int_{t0}^{ti} \Delta C_{Mg}\, dt + \upsilon_{cal} \int_{t0}^{ti} (\Delta C_{Ca} - \Delta C_{Mg})\, dt \right)$$

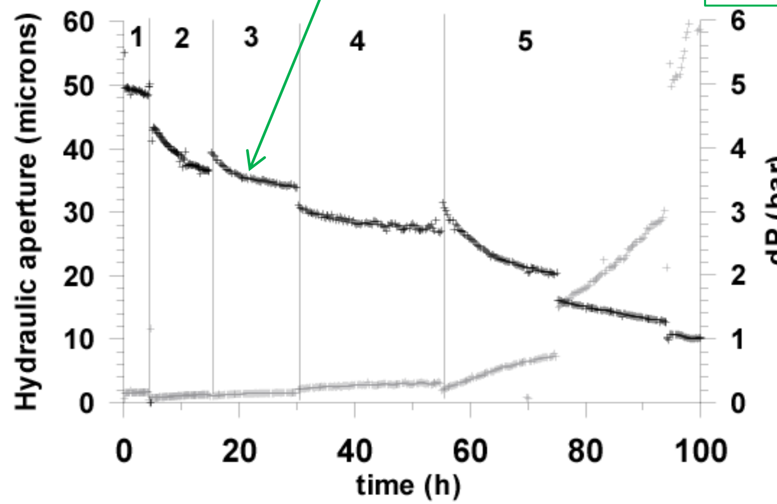
a_c calculated from chemical analysis



$$a_m = \langle a \rangle_{yz} = \frac{1}{L\, l} \int_{y=0}^{l} \int_{z=0}^{L} a(y,z)\, dy\, dz$$

a_h calculated from Darcy's law

$$a_h = \sqrt[3]{\frac{12\, \mu\, L\, Q}{\Delta P\, l}}$$



(Noiriel *et al.*, WRR, 2007)

Rough fracture dissolution with coating growth (marl)

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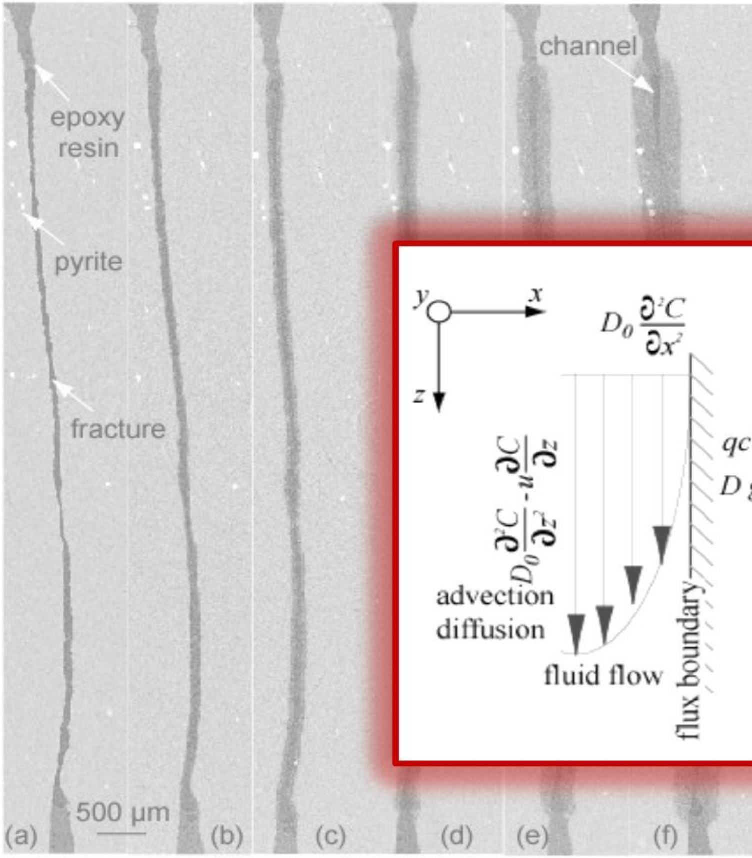
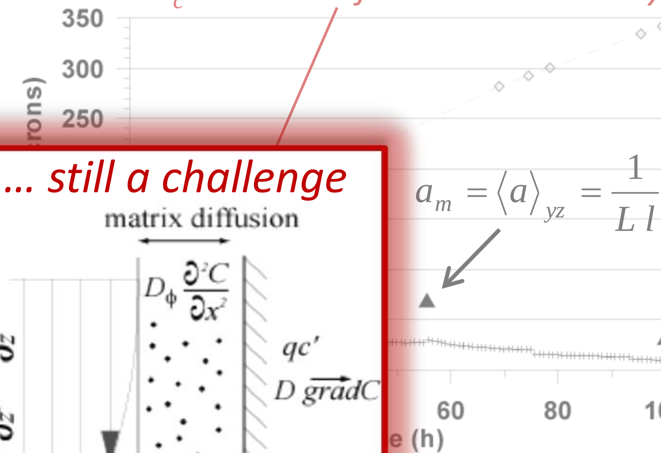
a_c *calculated from chemical analysis*





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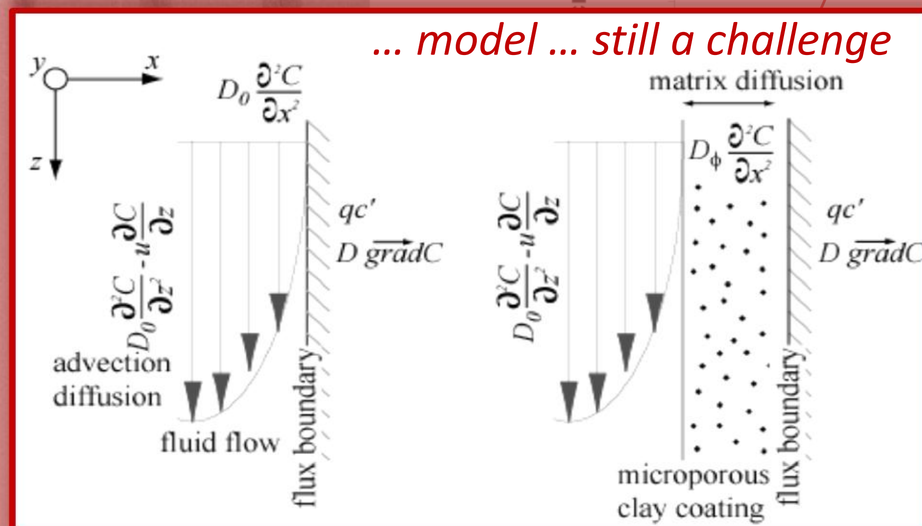
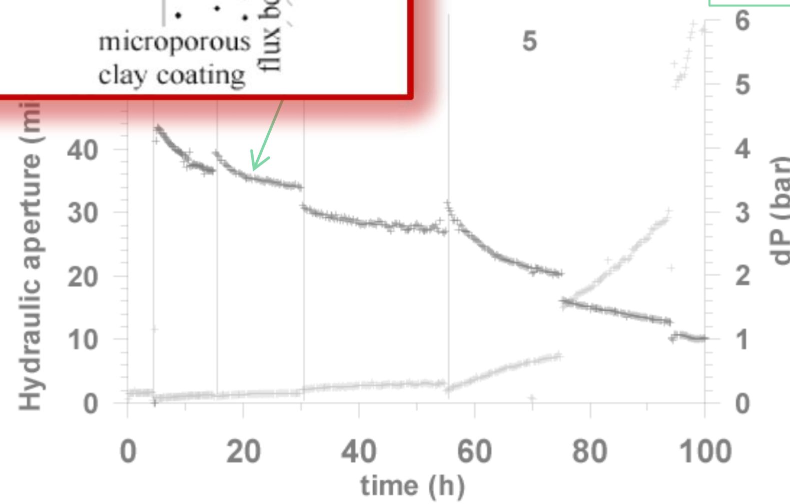
... model ... still a challenge



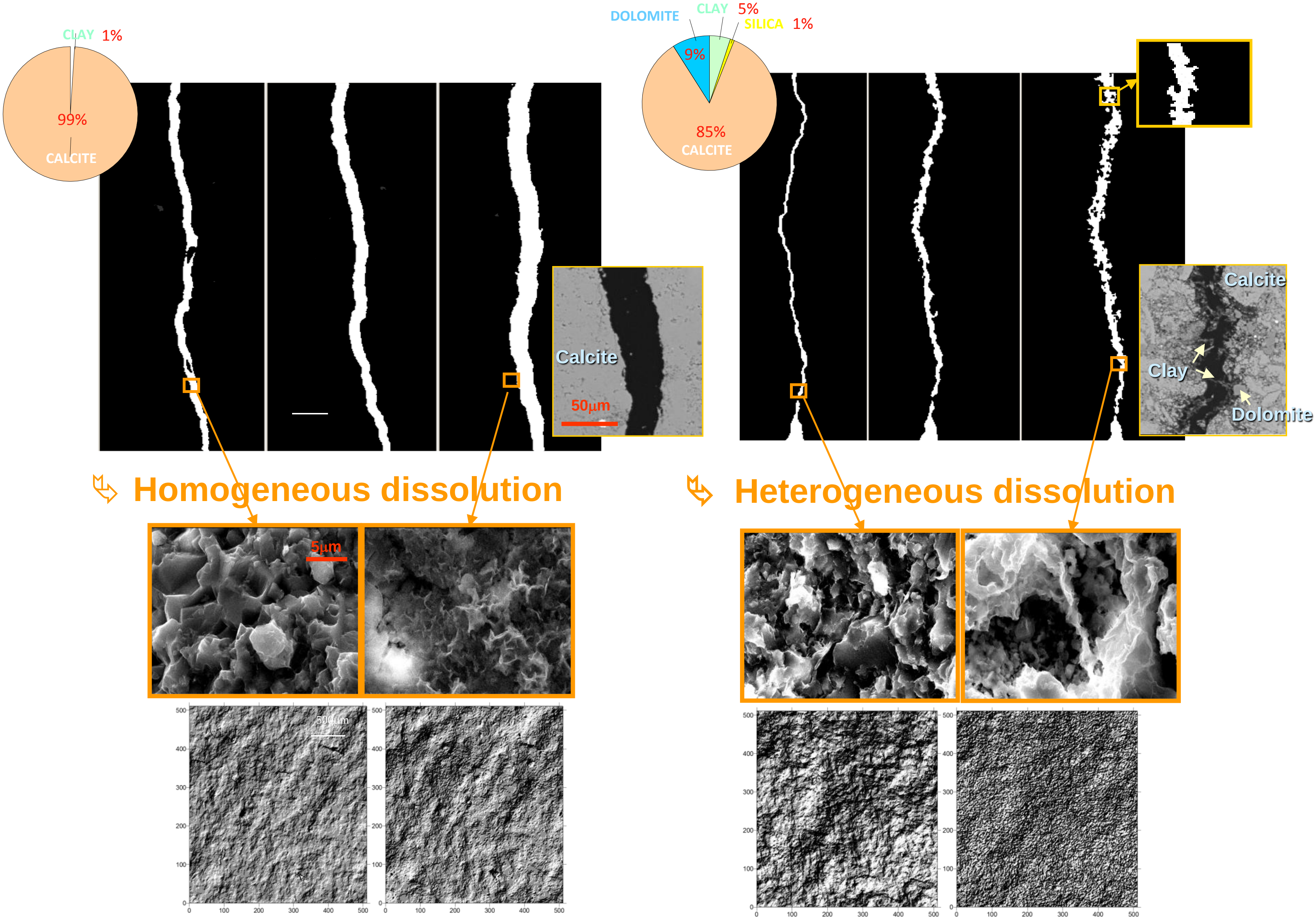
l from Darcy's law

$$a_h = \sqrt[3]{\frac{12\, \mu\, L\, Q}{\Delta P\, l}}$$



(Noiriel *et al.*, WRR, 2007)

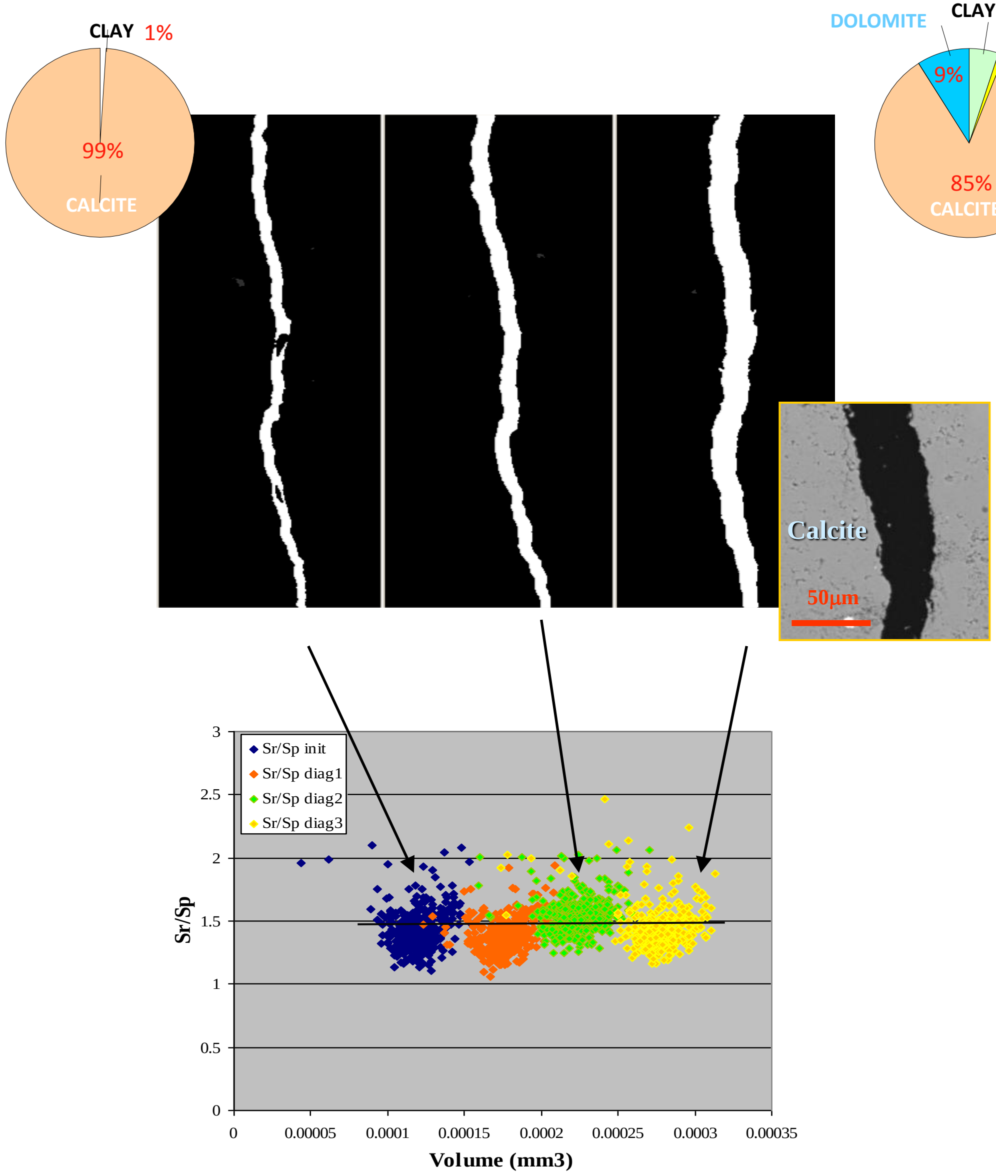
Rough fracture dissolution: effect of differential kinetics

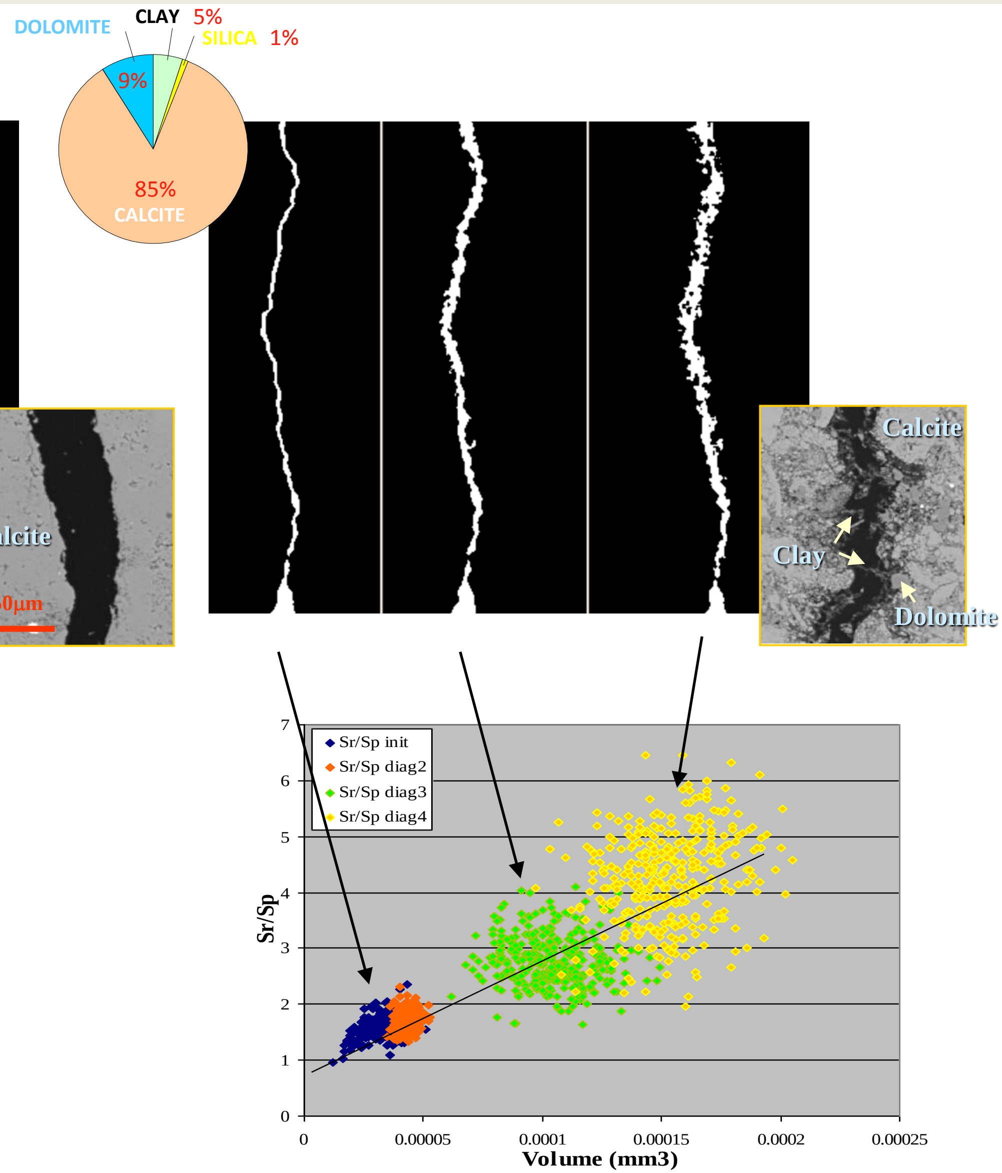


Fractal dimension: 2.2 → 2.2 2.2 → 2.4

(Gouze *et al*, GRL, 2003)

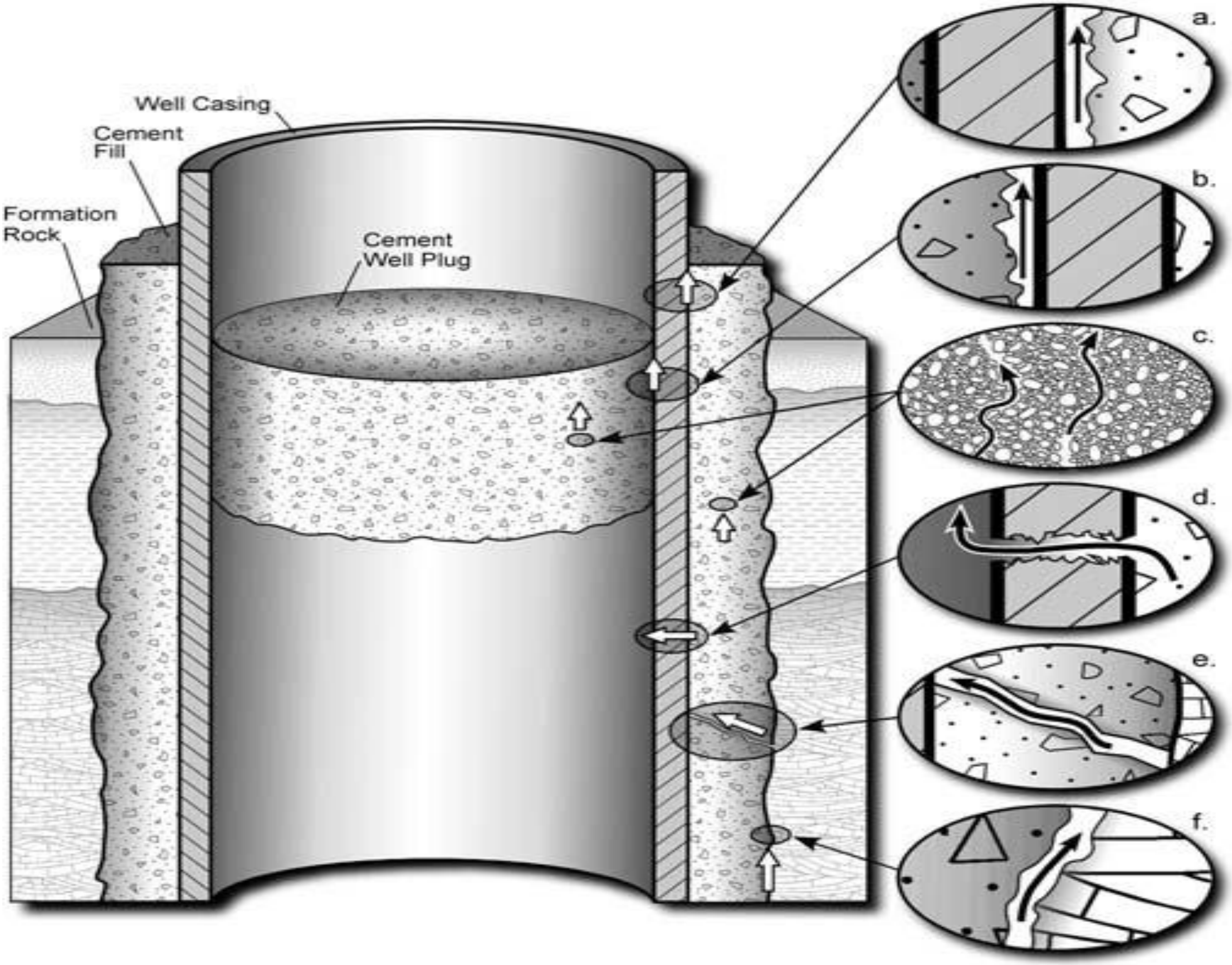
Rough fracture dissolution: effect of differential kinetics





(Gouze *et al*, GRL, 2003)

Alteration of fractured class G well cements



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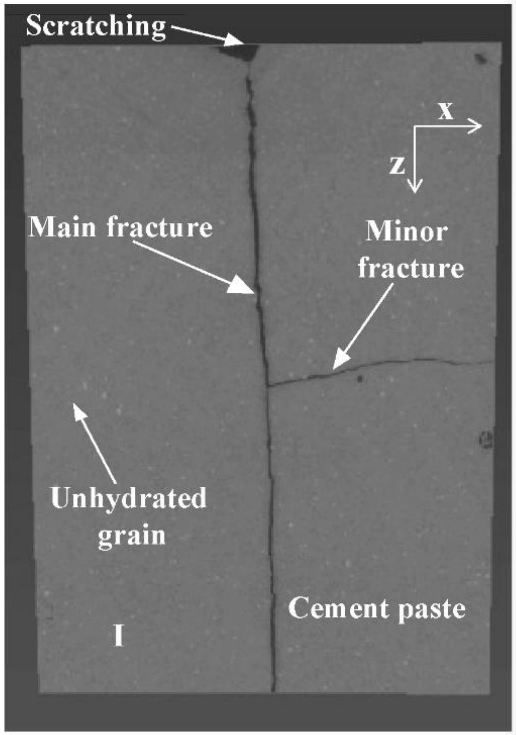
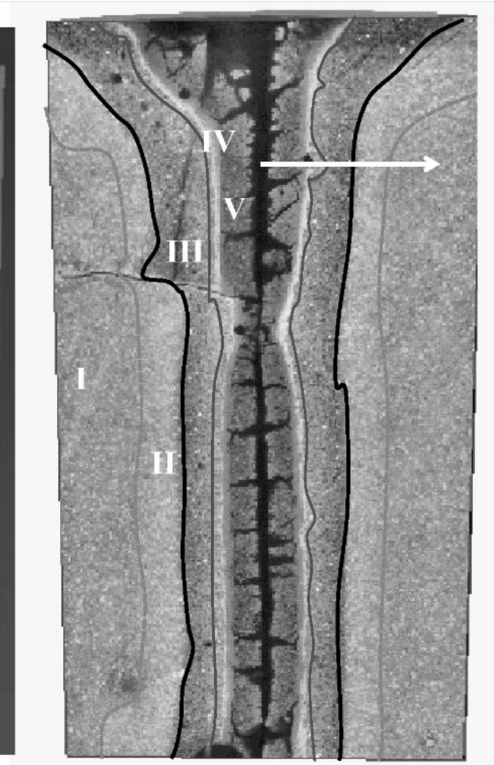
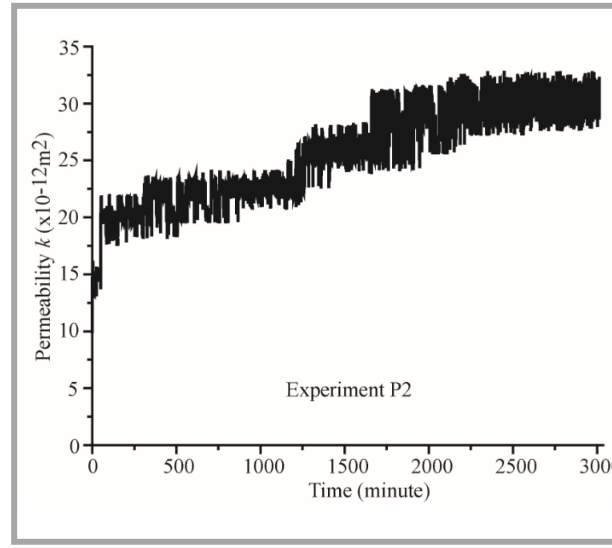
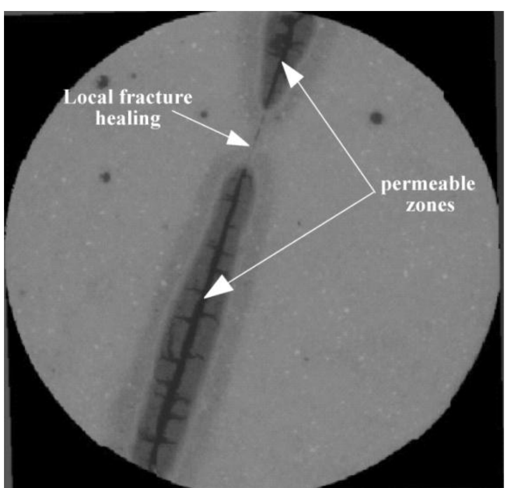
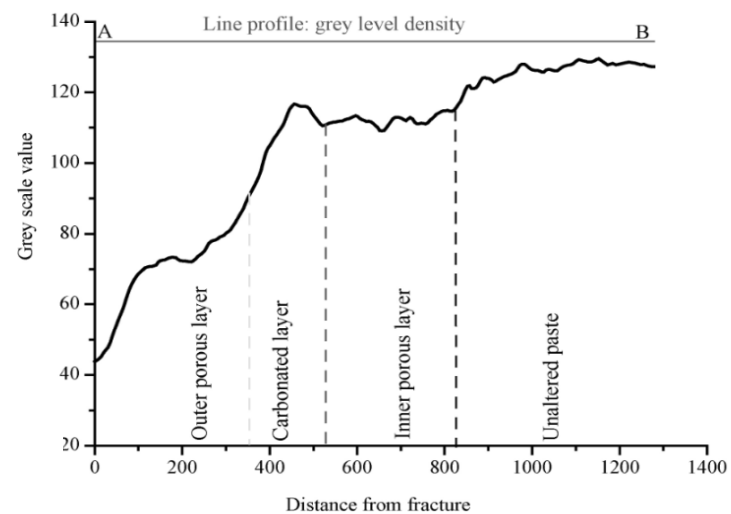


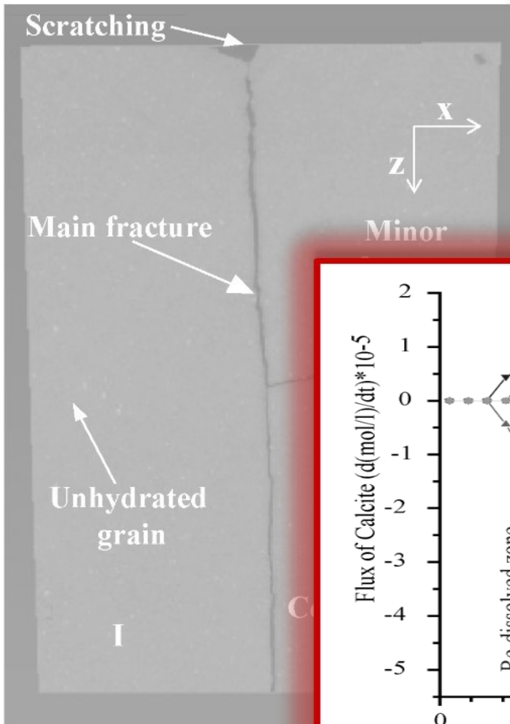


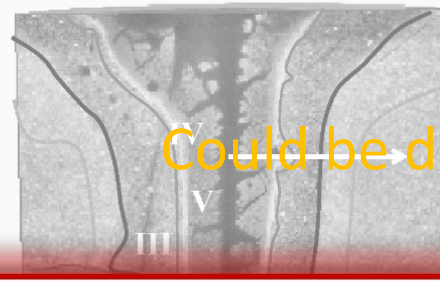




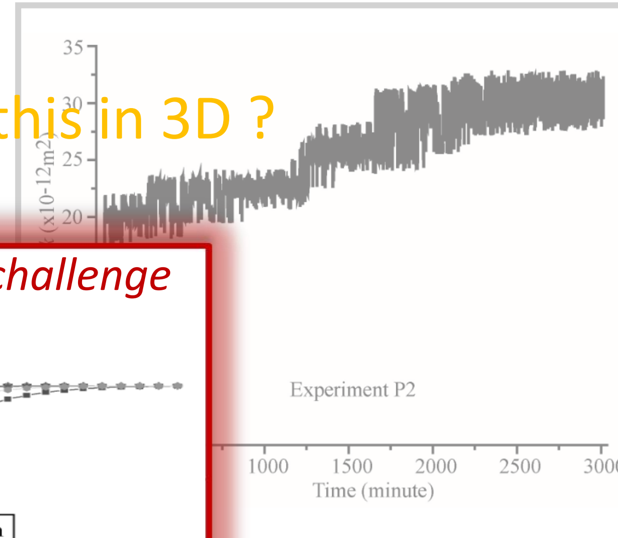


Alteration of fractured class G well cements

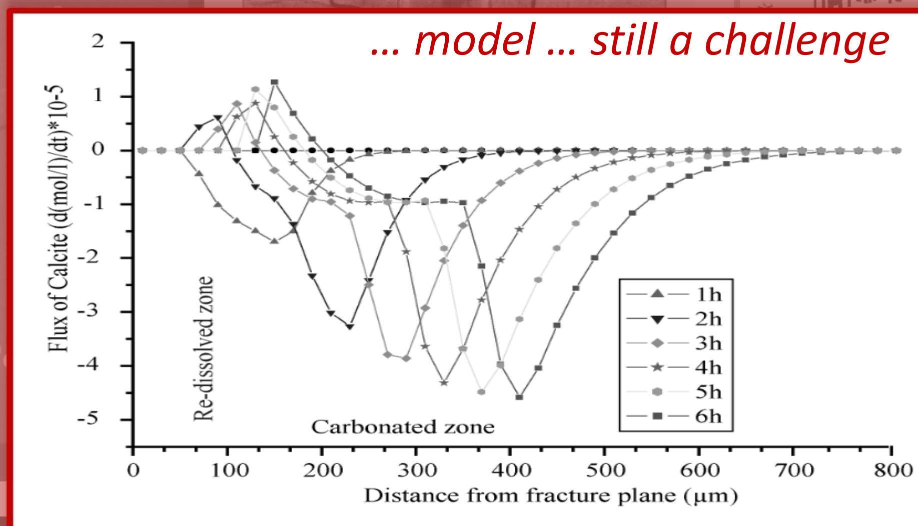


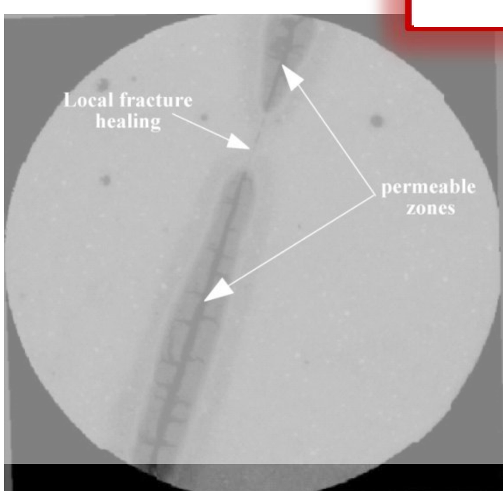


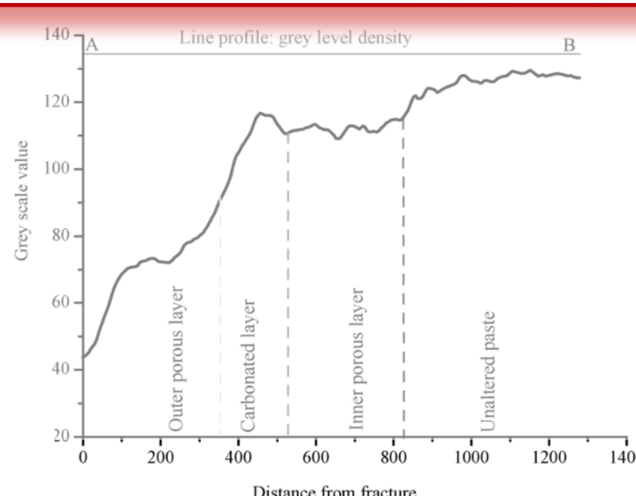
Could be do this in 3D ?



... model ... still a challenge



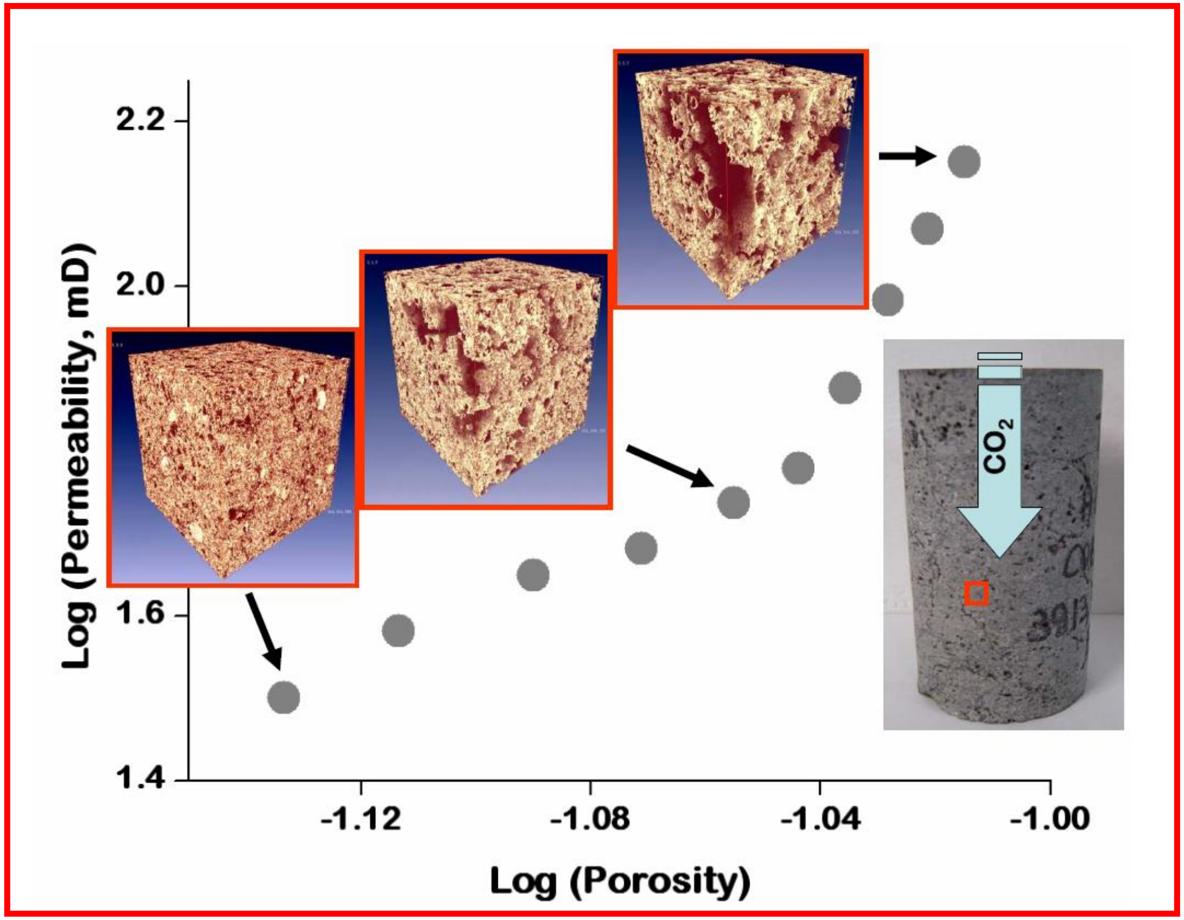




Porous media

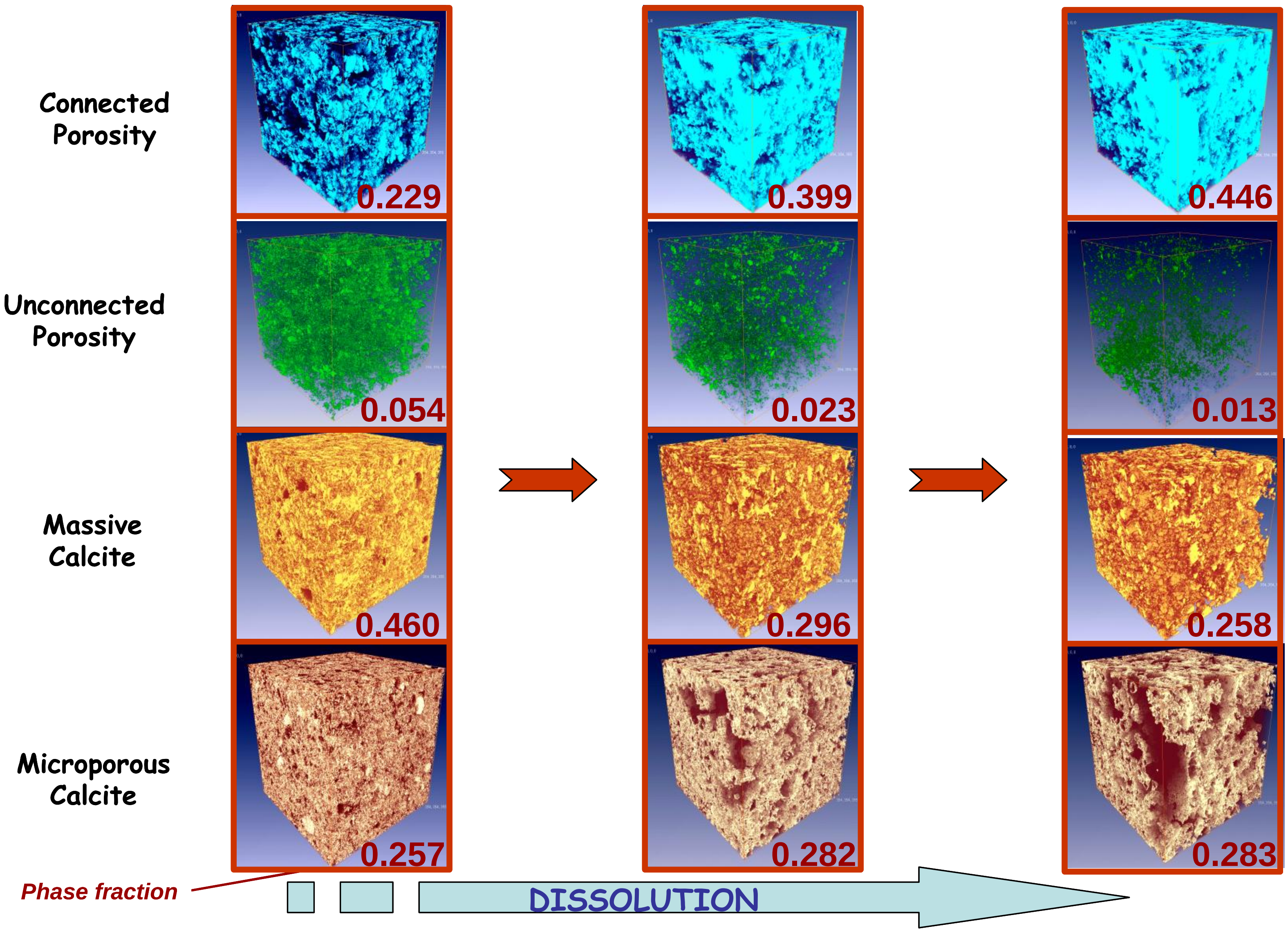
Characterization of the dissolution/precipitation processes in the reservoir

Main issue for model = poro-perm relationship

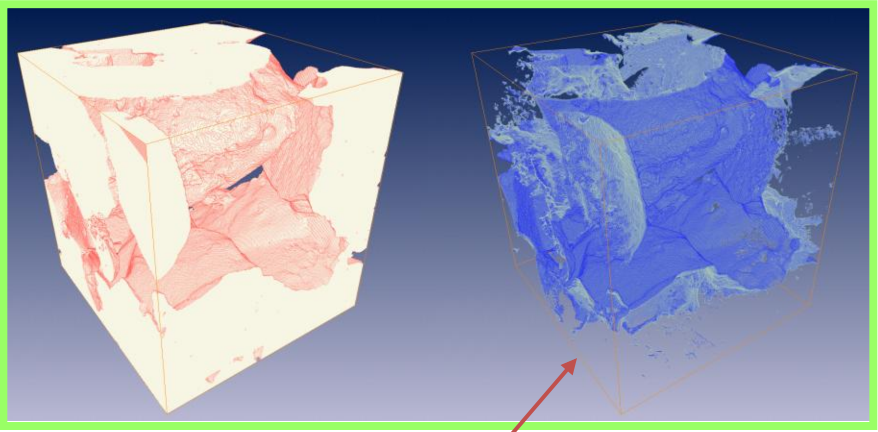


(Luquot & Gouze, CG, 2009)

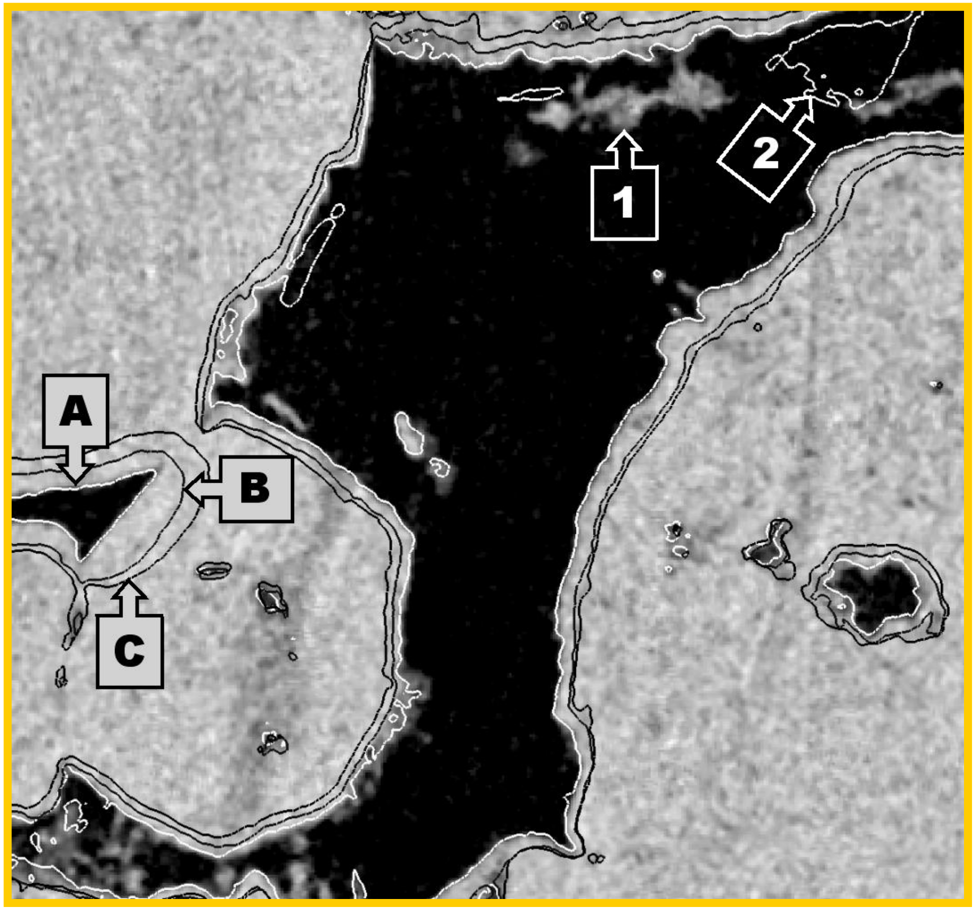
Characterization of the dissolution/precipitation processes in the reservoir



Characterization of the dissolution/precipitation processes in the reservoir



Cumulative volume of rock dissolved at the end of the experiment

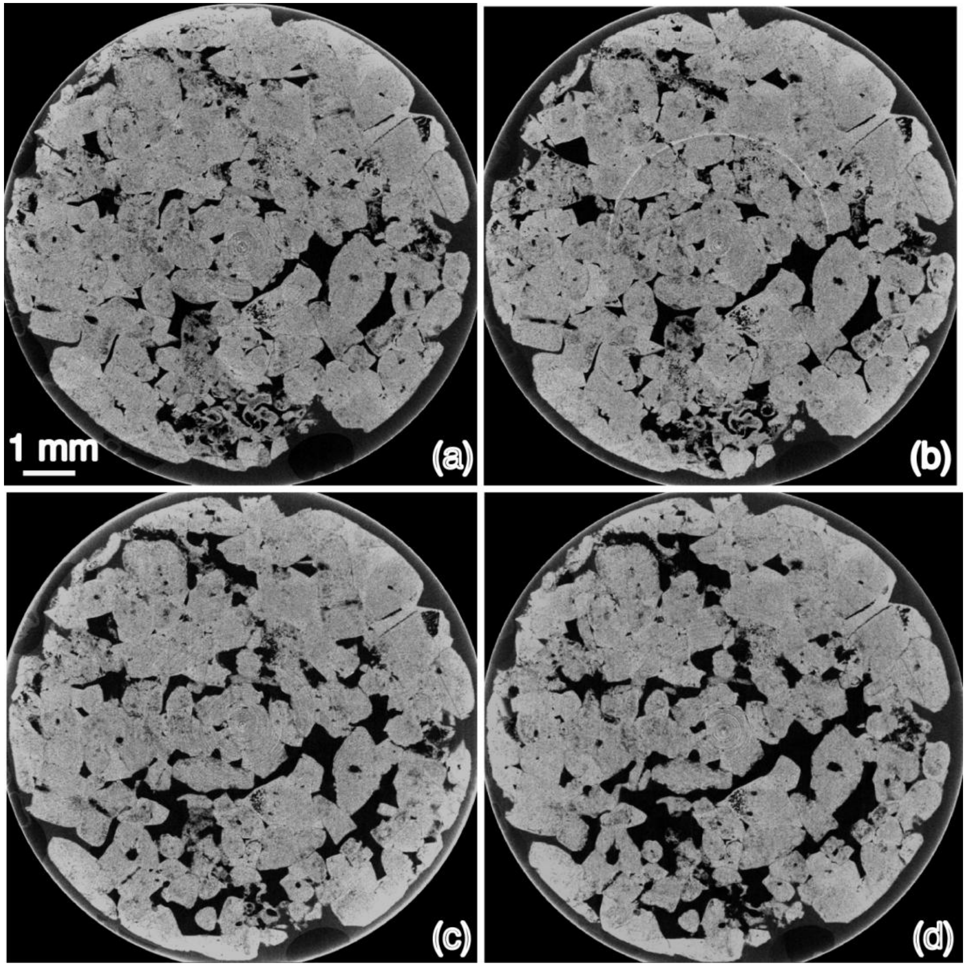


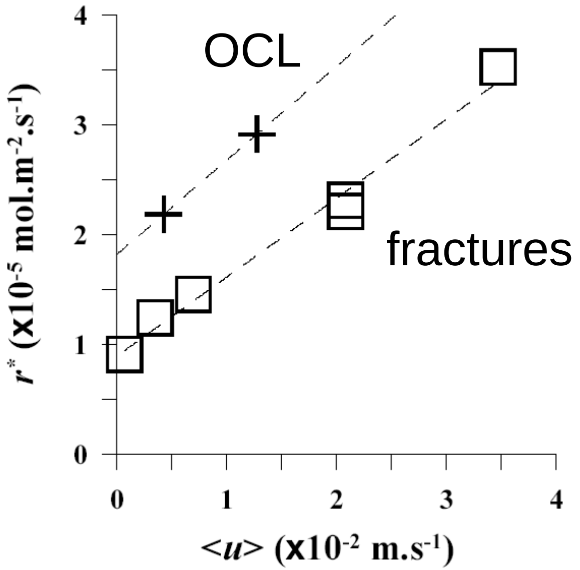
(Noiriel *et al.*, GRL, 2004)

Characterization of the dissolution/precipitation processes in the reservoir …

and measuring effective dissolution rate and kinetics parameters

Oxfordian crinoïdal limestone (OCL)





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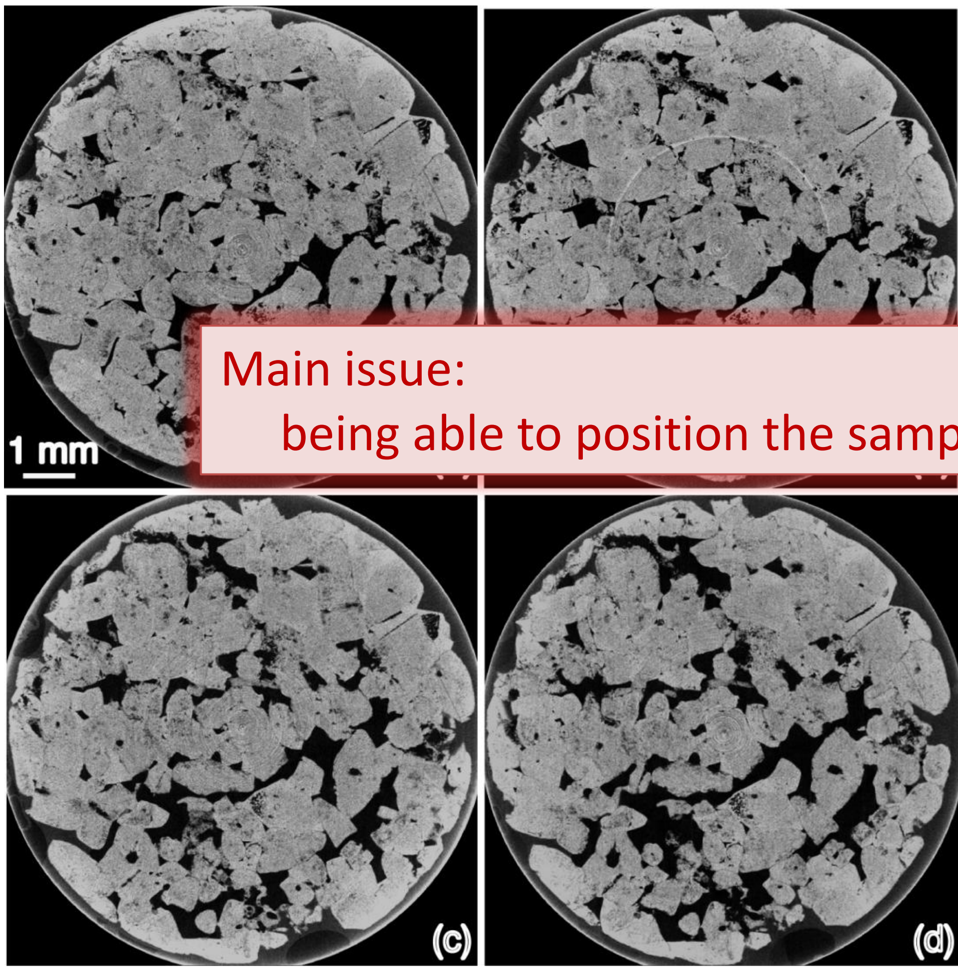
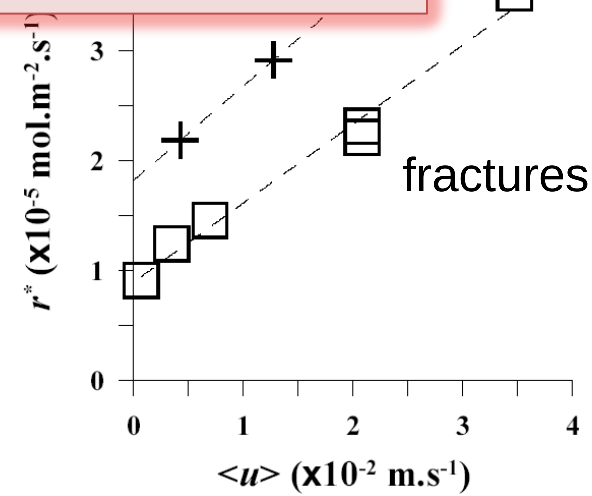
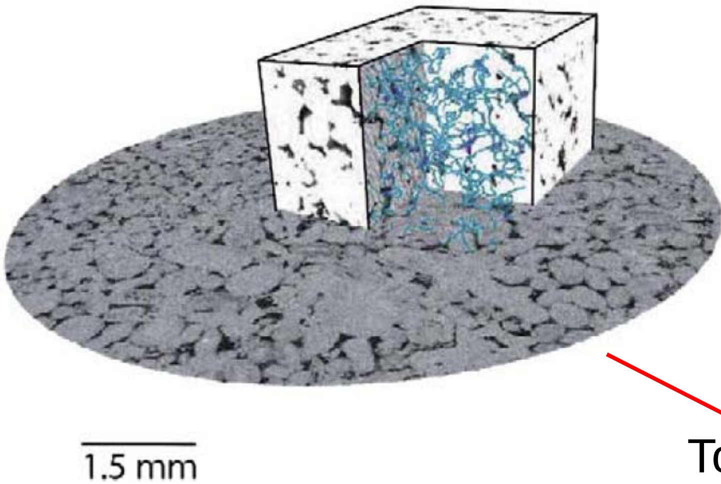


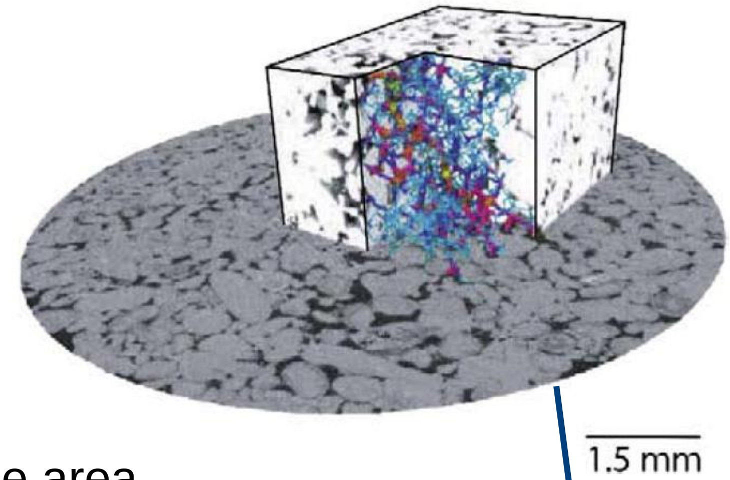
Main issue:
being able to position the sample at ± 1 pixel size in 3D



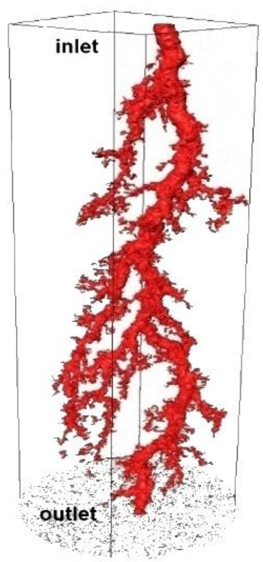
(Noiriel *et al.*, GRL, 2004)

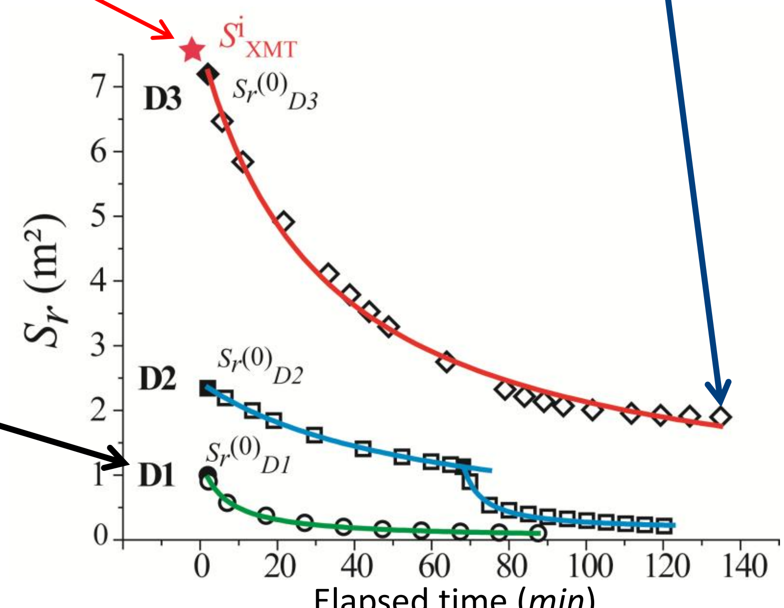
and measuring effective reactive surface area





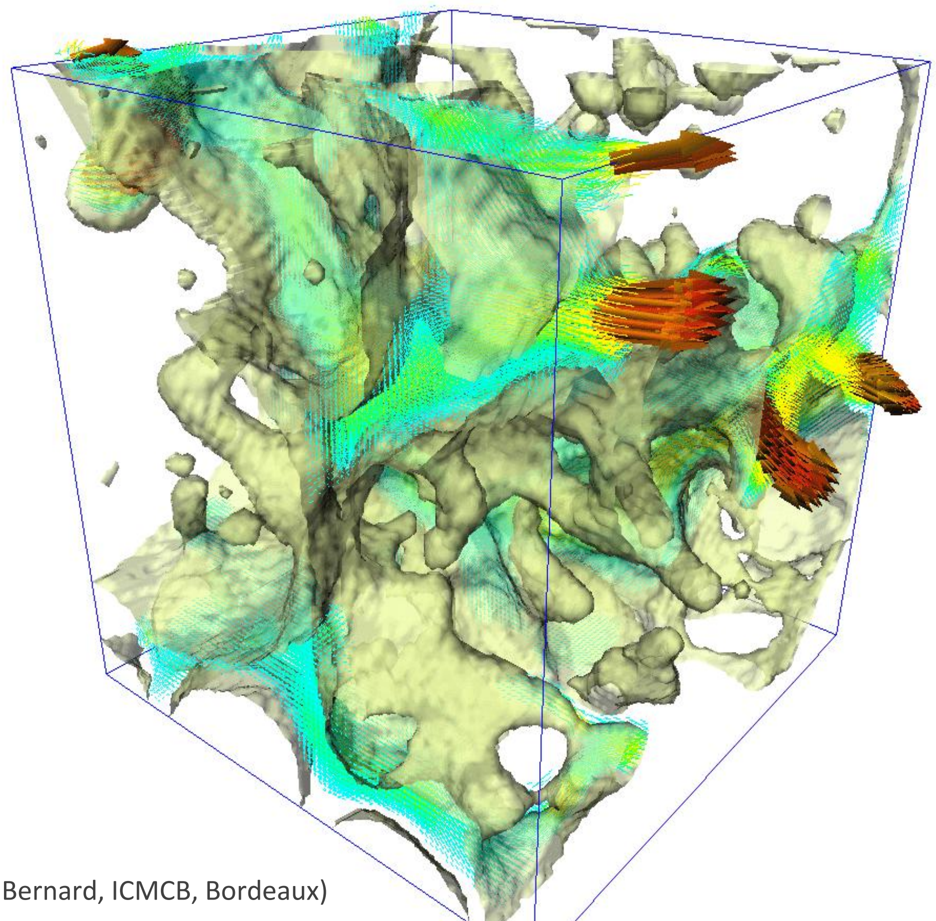
Total interface area

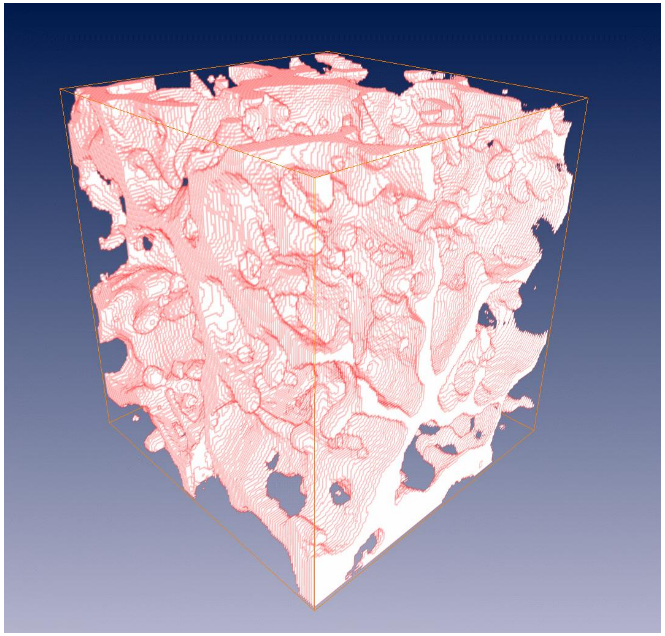




(Gouze & Luquot, JCH, 2010)

Compute permeability tensor



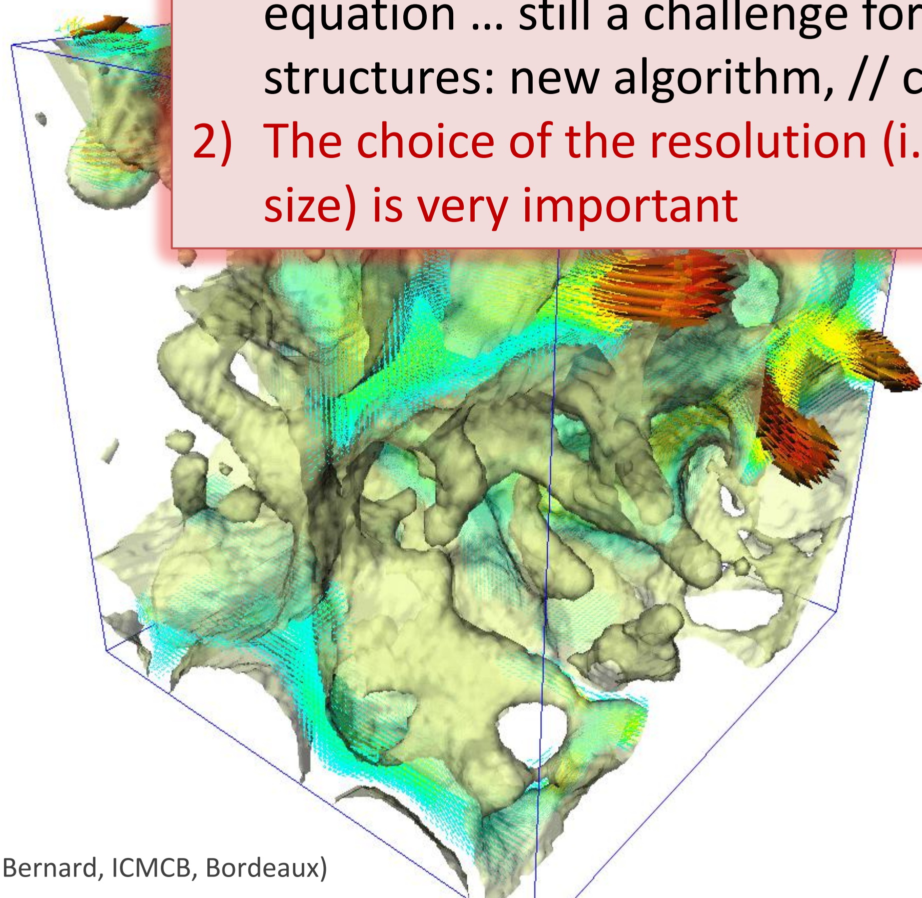


$$K_{ij}$$

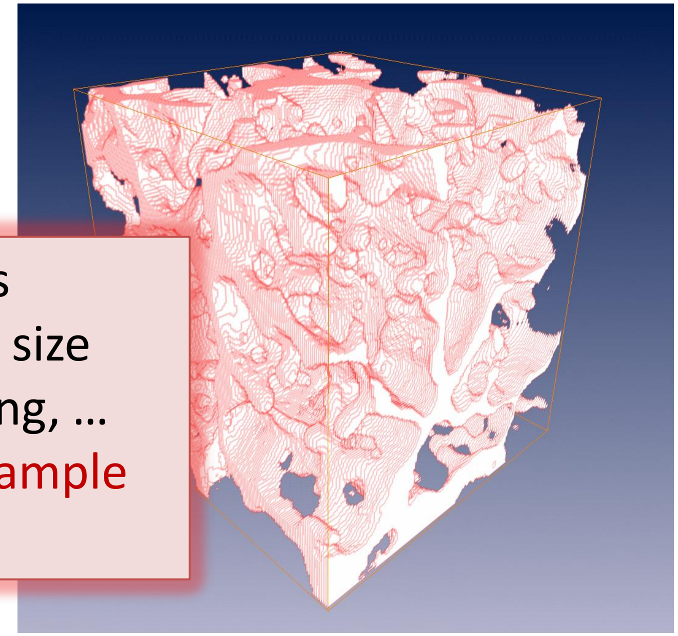
$$\begin{vmatrix} 1.216 & 4.77\ 10^{-3} & 1.90\ 10^{-2} \\ 4.78\ 10^{-3} & 1.227 & -0.173 \\ 1.90\ 10^{-2} & -0.173 & 1.046 \end{vmatrix}$$

(PC, Bernard, ICMCB, Bordeaux)

Compute permeability tensor



1) Meshing and then compute the Stokes equation … still a challenge for “large” size structures: new algorithm, // computing, …
2) The choice of the resolution (i.e. the sample size) is very important



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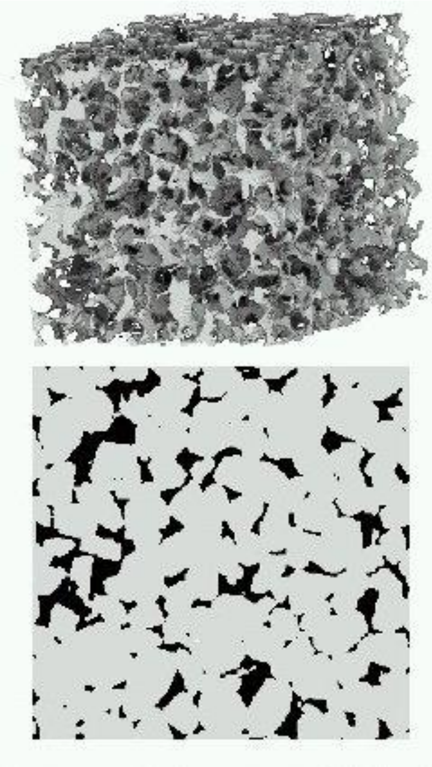
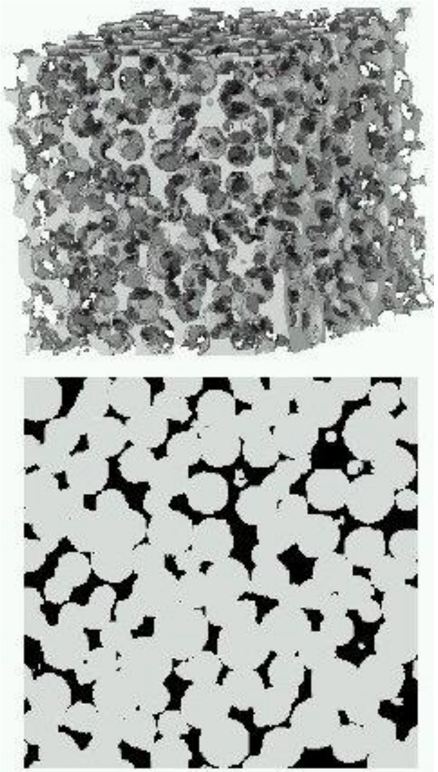
(PC, Bernard, ICMCB, Bordeaux)

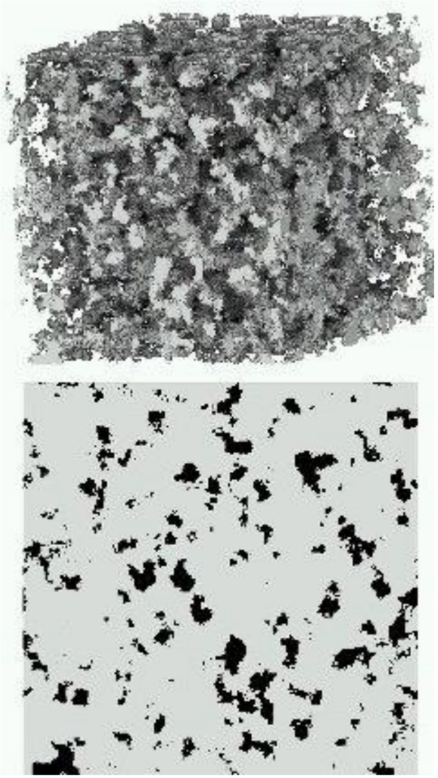
Use properties for generating statistically equivalent porous media



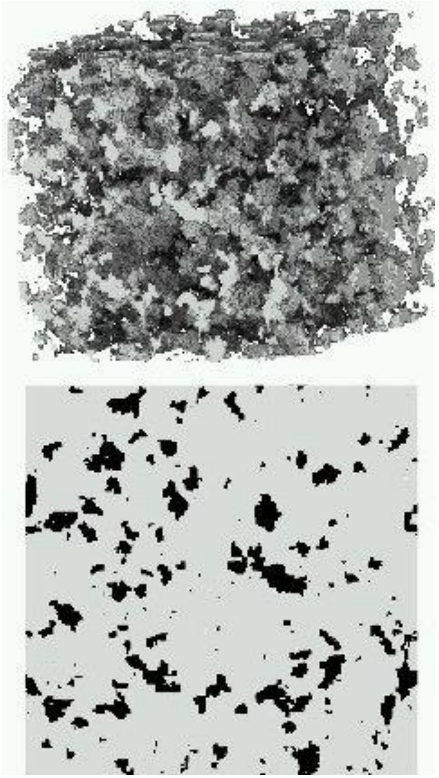
MicroCT



Process-based

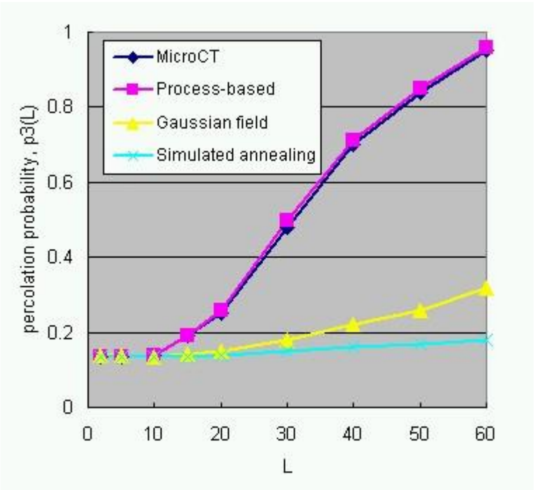


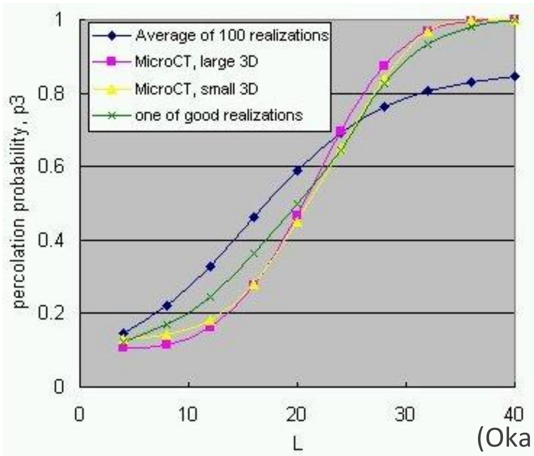
Gaussian-field



Simulated Annealing

(Biswal et al., Phys. A,1999)

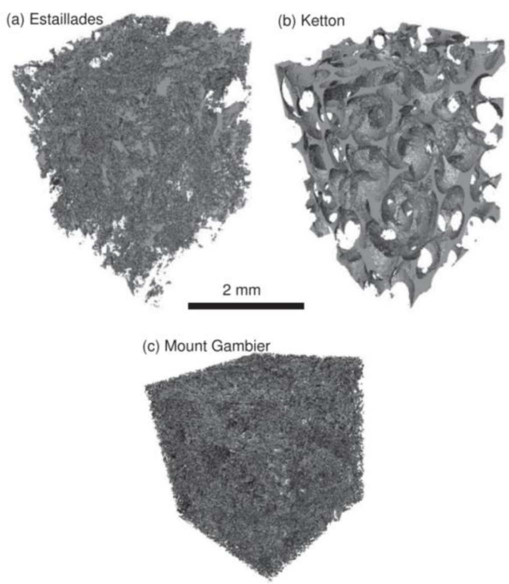




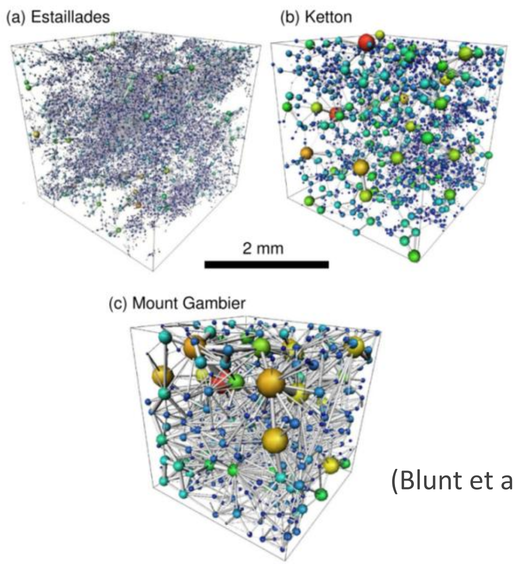
(Okabe and Blunt, PS&E., 2005)

Construction of pore network models

Objective: simplifying computations for flow and transport by using much simple geometries.



Micro CT

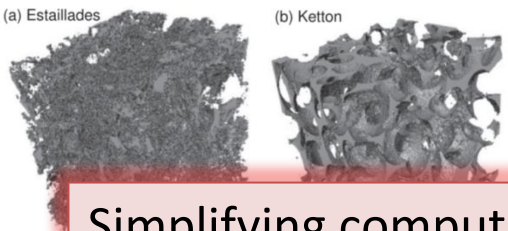


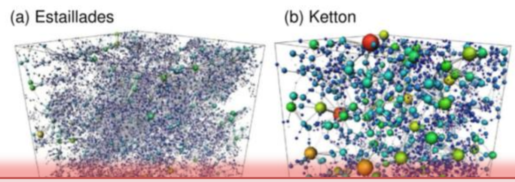
(Blunt et al., AWR, 2005)

Pore networks extracted from the images

Construction of pore network models

Objective: simplifying computations for flow and transport by using much simple geometries.





Simplifying computation for flow and transport?

yes if

1) fully reversible skeletonization
2) structure characterization over 5 to 6 order of magnitude

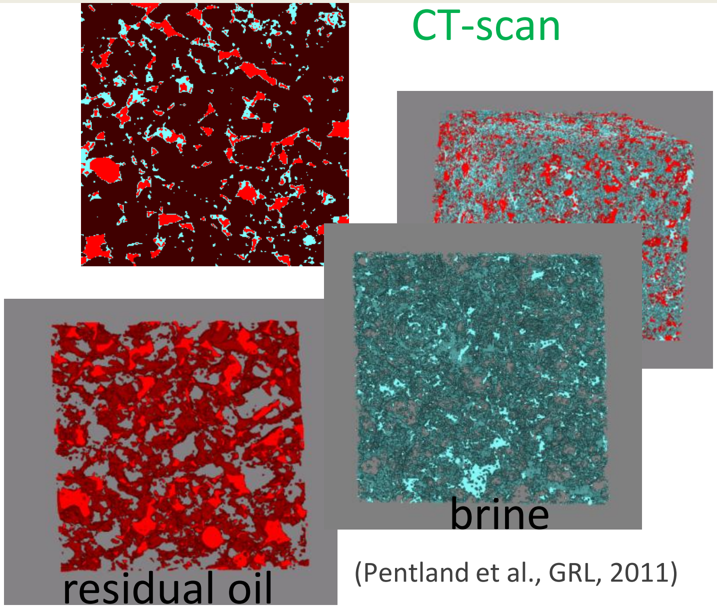
ex: sample 10^{-2} m => tomo @ 5×10^{-6} m ,

then, zoom-in @ 5×10^{-7} m

or, zoom-in @ 5×10^{-8} m !)

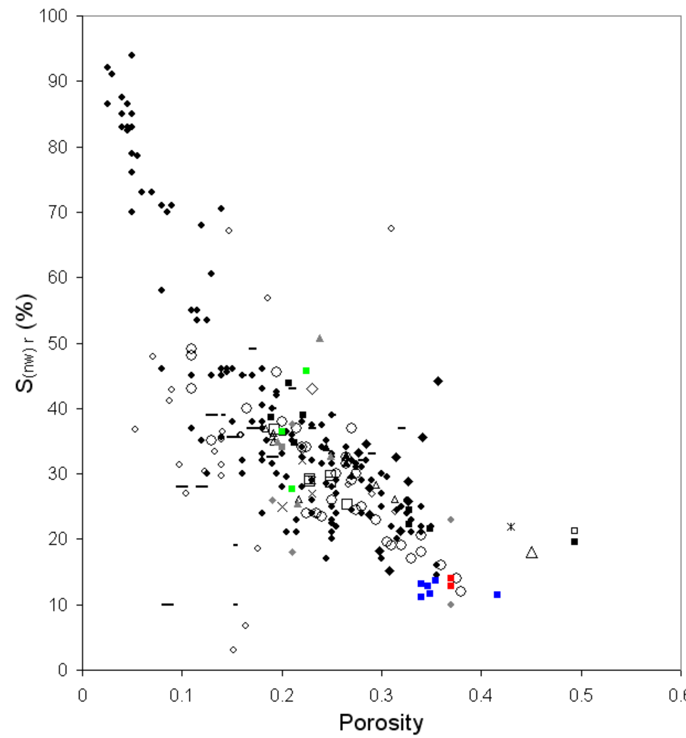
Multiphase flow ….

CT-scan

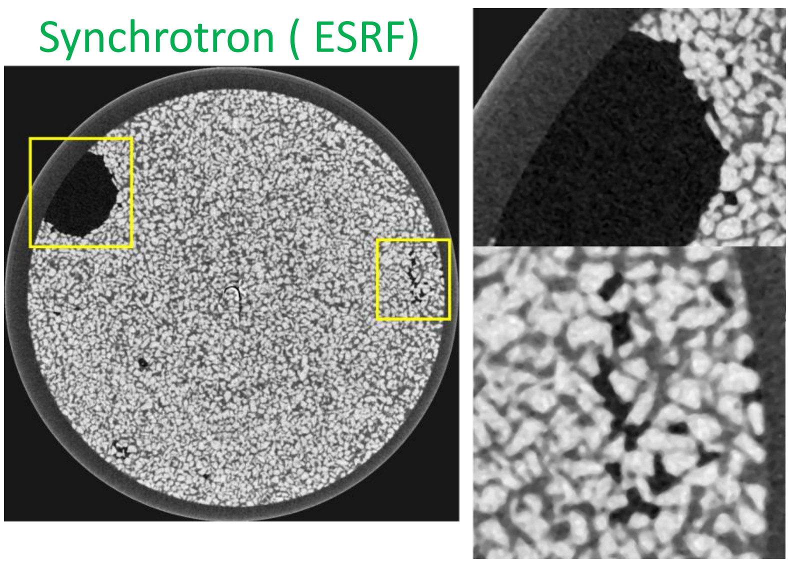


(Pentland et al., GRL, 2011)

Objective: measure residual saturation & relative permeability

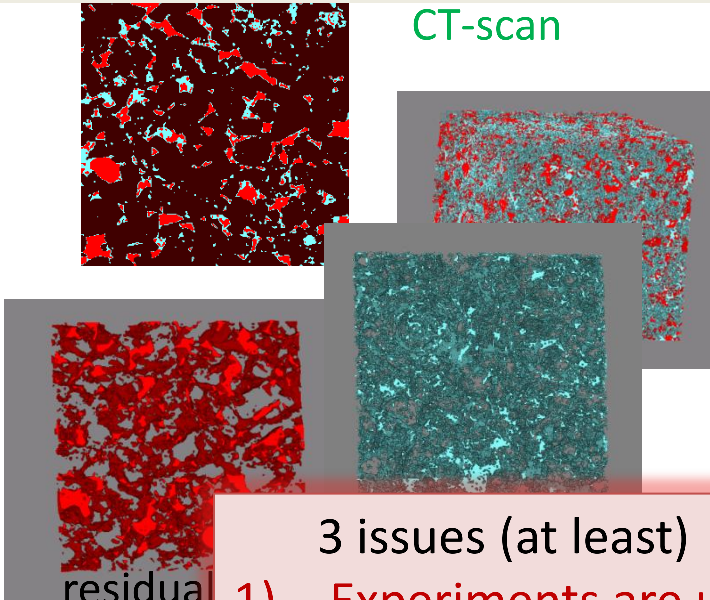


Synchrotron (ESRF)



Multiphase flow ….

CT-scan



Objective: measure residual saturation
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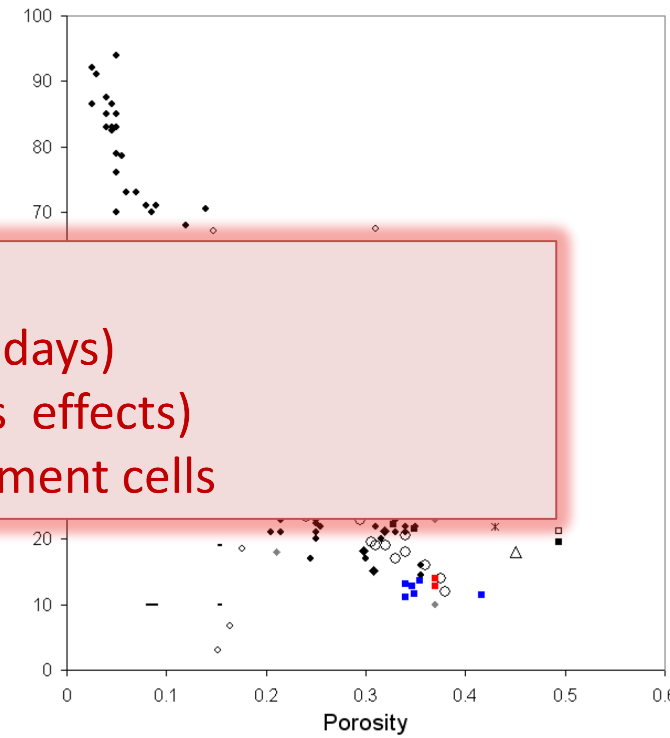
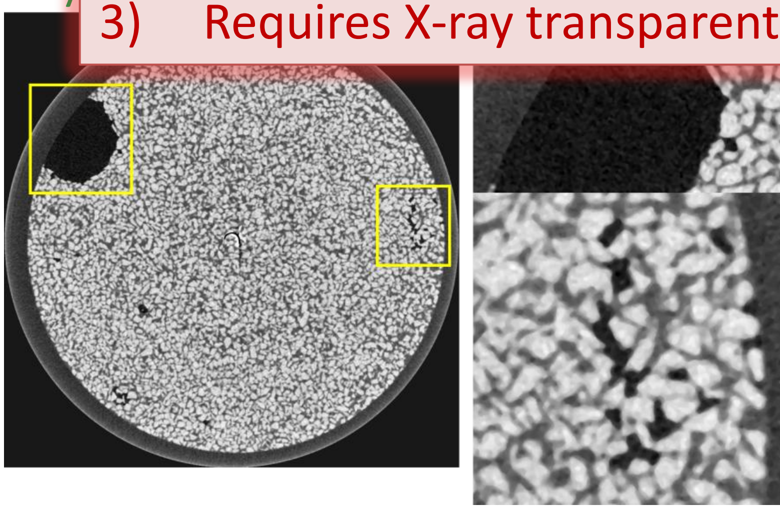
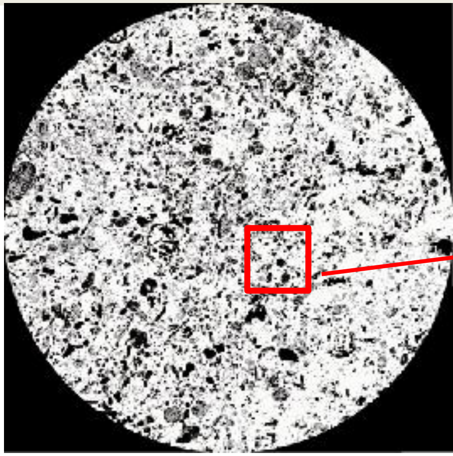




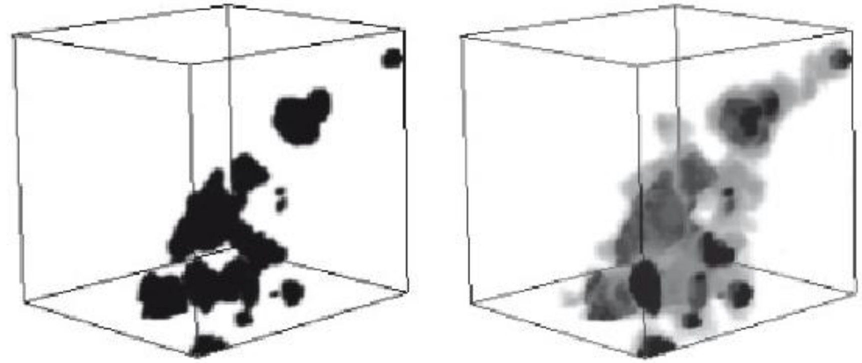
3 issues (at least)

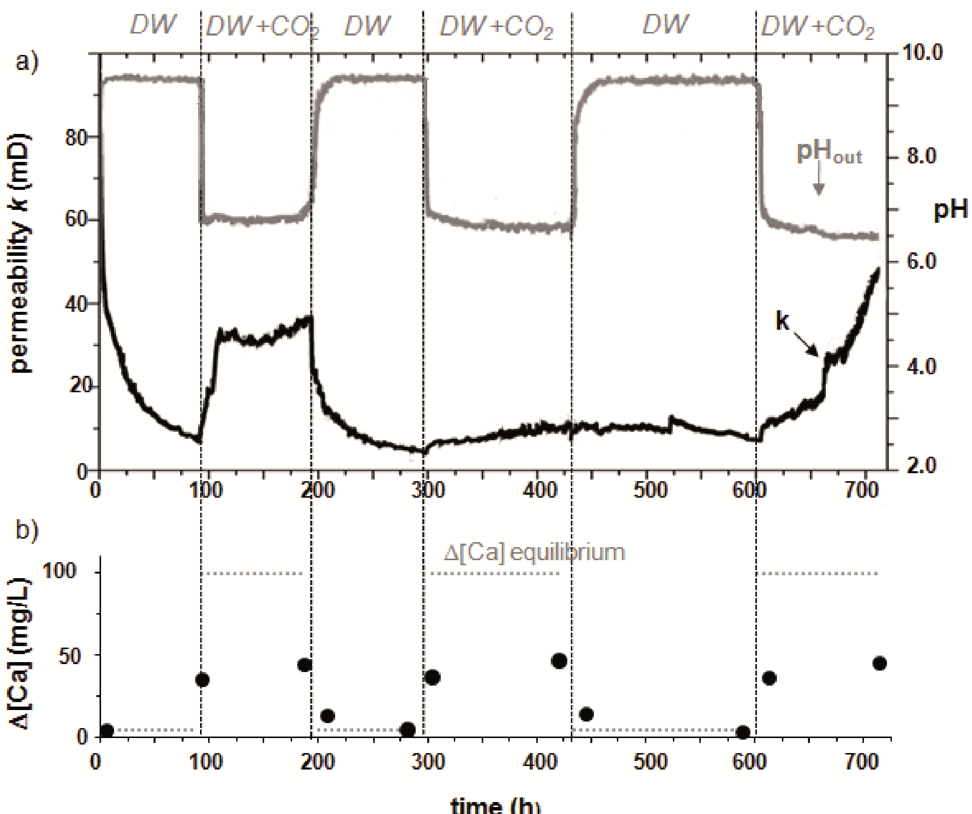
1) Experiments are usually long (1 – 2 days)
2) Problem with water (local radiolysis effects)
3) Requires X-ray transparent confinement cells

Dissolution and particles transport in carbonates



Pores > resolution   pores < resolution (μ–porosity)





Porosity always increases
(i.e. solid mass is removed)
but

Permeability may increase or decrease depending on the pH of the fluid.

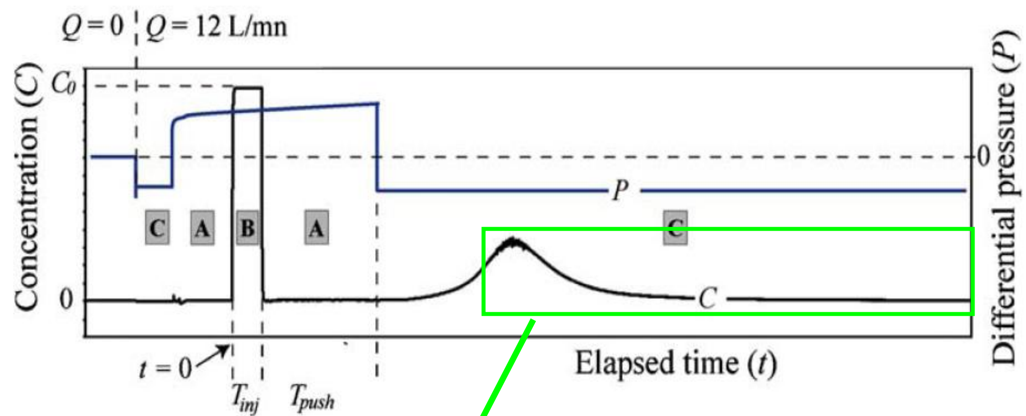
$\Rightarrow$ Calcite μ-grains detached and moved instead of being dissolved

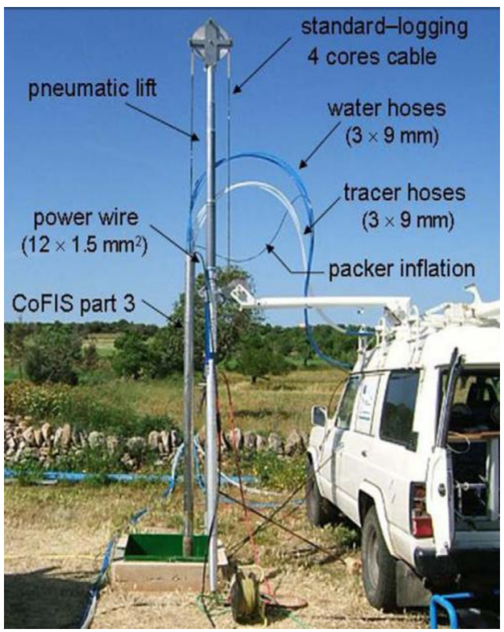
(Garing et al., subm.)

Applications to subsurface processes (dispersion of pollutants)

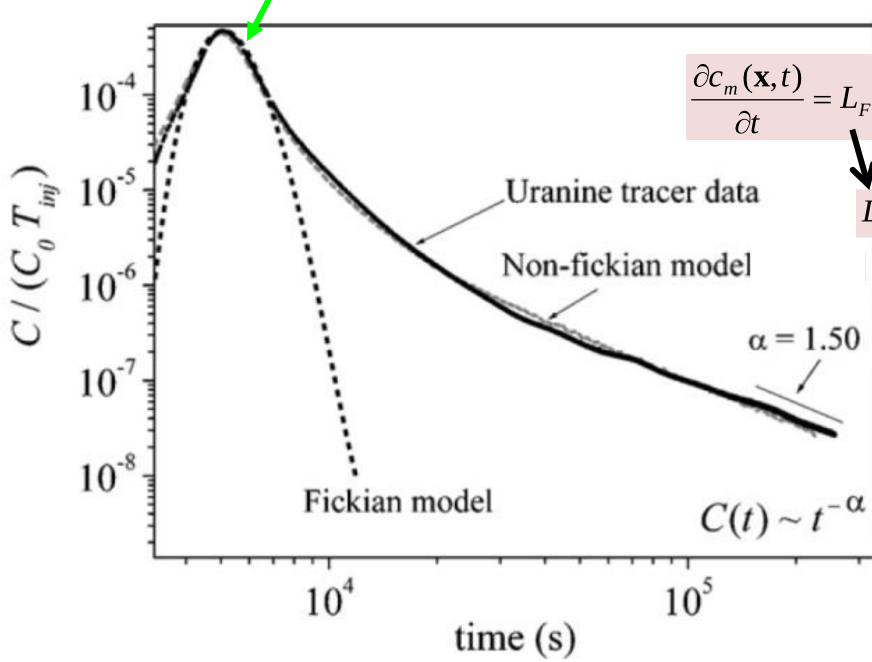
A main issue :
Explain the always-observed non-Fickian dispersion behavior
(while all models assume Fickian dispersion)

1) Field scale experiment





Breackthrough curve (BTC)

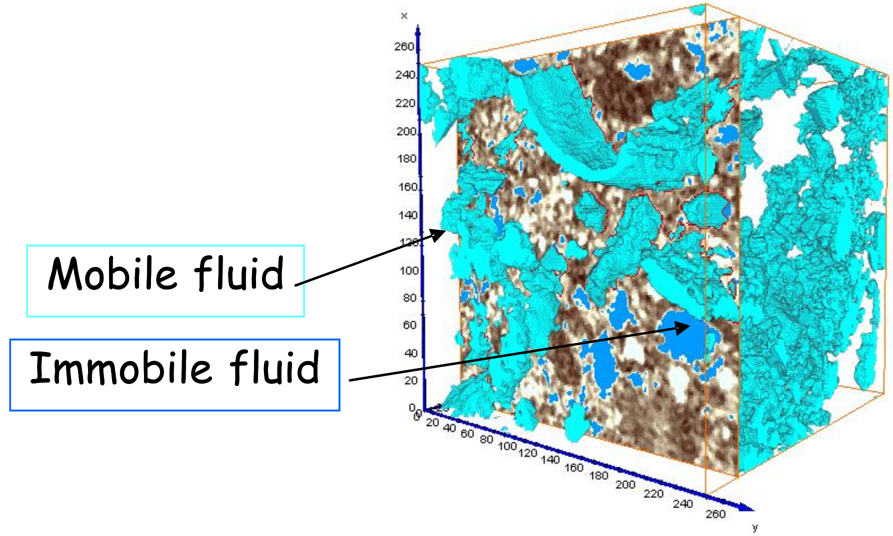


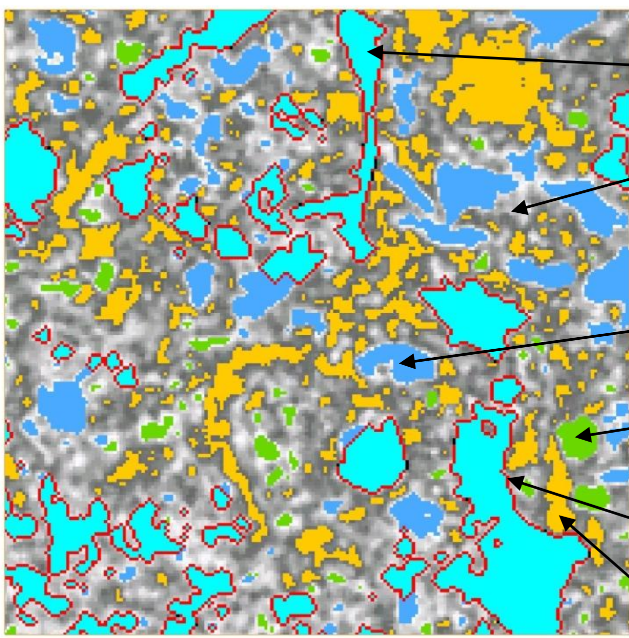
$$\frac{\partial c_m(\mathbf{x},t)}{\partial t} = L_F(c_m) - \beta\int_o^t G(t')\frac{\partial c_m(t-t')}{\partial t}\,\mathrm{d}t'$$

$$L_F(c_m) = \nabla.(\mathbf{D}\nabla c_m - \mathbf{u}c_m)$$

(Gouze et al, WRR, 2008, 2009)

2) XRMT of the rock samples and specific data processing





Mobile domain (advection - dispersion)

Immobile domain

- Microporous matrix (diffusion $\phi d_0 / \tau$) => diffusion limited reaction
- Macro dead-ends (diffusion d_0)
- Trapped macroporosity (diffusion d_0)

Main reaction surface

Non diffusive fraction (solid)

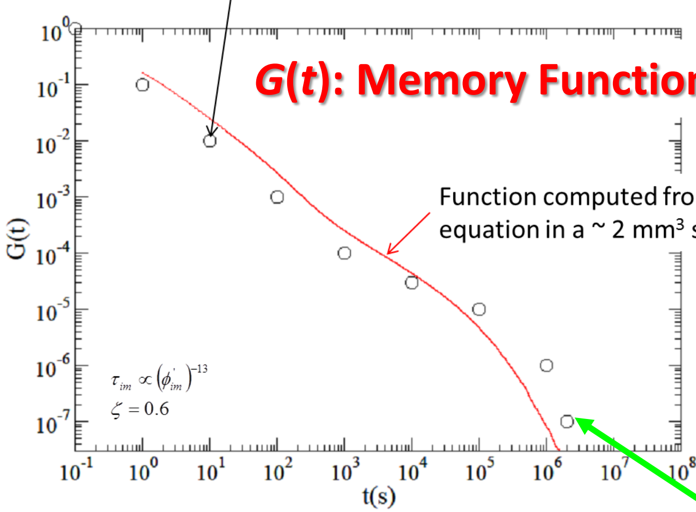
(Gouze et al, WRR, 2008, 2009)

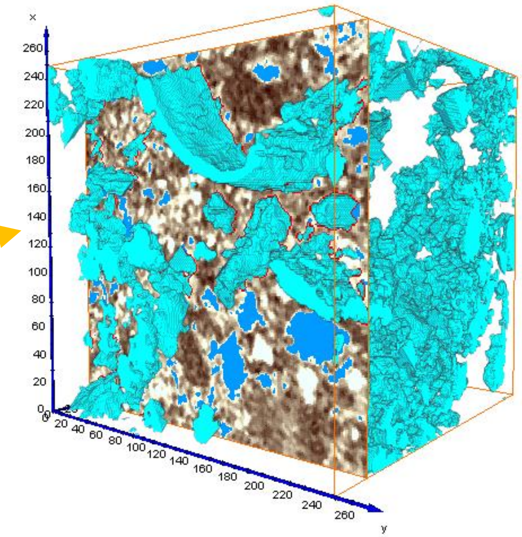
3) Compare $G(t)$ computed from the XRMT and $G(t)$ obtained from the field measurements

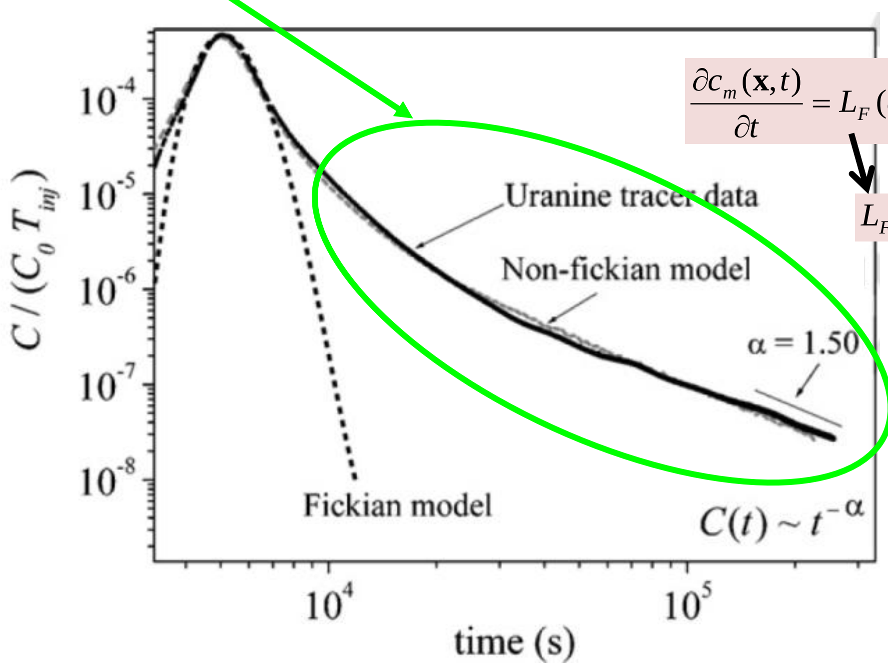
Function inferred from field-scale BTC (process scale ~ 1 *m*)

$G(t)$: Memory Function

Function computed from solving the diffusion equation in a ~ 2 mm³ sample (scale ~ 10^{-6} *m*)







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$$L_F(c_m) = \nabla.(\mathbf{D}\nabla c_m - \mathbf{u} c_m)$$

(Gouze et al, WRR, 2008, 2009)

Main issues

Media composition (mineral and void distribution)
Media structure versus flow properties
Media structure versus solute transport & reactions
Structure of fluid-fluid interfaces (multiphase flow)
Media structure versus mechanical properties

Requirements (not all achievable so far, or at least not simultaneously …)

3D !
Using samples of characteristic size around 1 cm.
Large range of scales (resolution from sub-100nm to tens of microns)
Fast imaging for allowing dynamic experiments
Resolving low contrast interfaces
Resolving mineral composition

If you think about the unique capabilities of SRX

what experiment comes immediately to your mind that you would like to do?

Static multi scale observations (zooming-in)

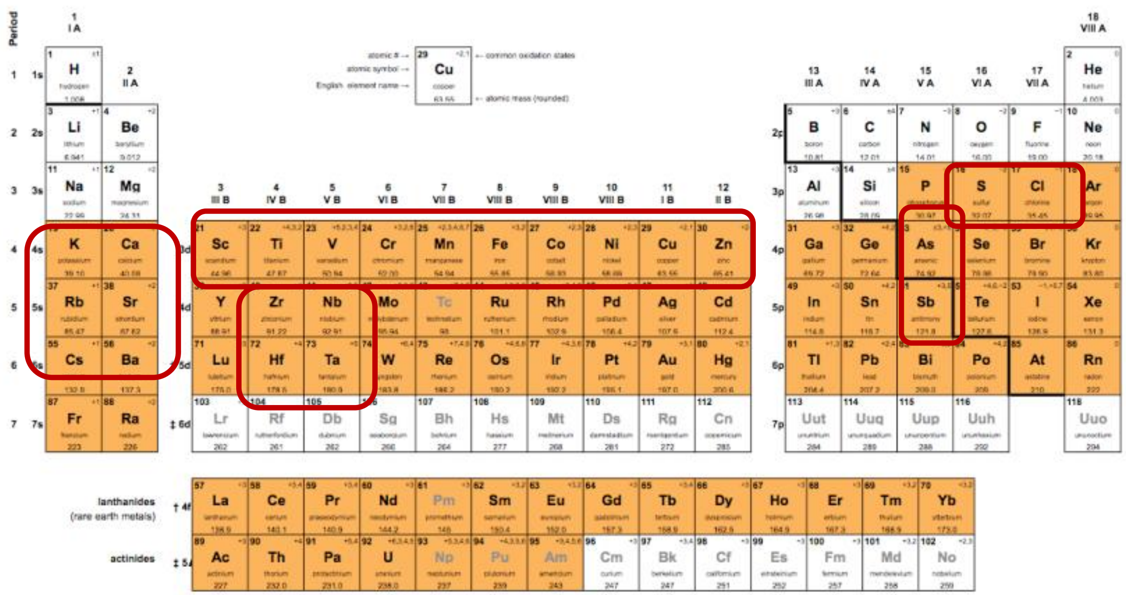
Dynamic experiments (monophasic and multiphasic fluid flow in porous media)

How should the sample environment look like?

What would be the demands on the environment from your samples?

For dynamic experiment, we need to build specific confinement cells (aluminum, carbon, …?)

Which elements with absorption edges in the energy range covered by SRX (4.65keV to 22keV) would be of most interest for you?



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What would be more important for you for an experiment at SRX, very high spatial resolution (sub-100nm) or a large sample area (mm with sub-micron resolution)?
The ideal for us is from sub-100nm to 5 microns (using “zooming in)


THANK YOU
H2O Com3
CO2 Com4